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Meteorology and Air Quality Modeling in Complex Terrain: A Literature Review

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METEOROLOGY AND AIR QUALITY MODELING IN COMPLEX TERRAIN
A Literature Review

by

Gerard A. DeMarrais and Terry L. Clark
Meteorology and Assessment Division
Environmental Sciences Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

ENVIRONMENTAL SCIENCES RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
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16. ABSTRACT

Modeling air quality in complex terrain has been and remains to be a difficult task simply because of the difficulty in parameterizing the complex wind flow regimes. Due to the complex terrain, significant submesoscale forces are established to perturb the mesoscale wind field. These forces must first be better understood and the algorithms must be developed to adequately simulate the effects of these forces before one can hope to reasonably model air quality in complex terrain. This literature review summarizes over 250 studies of meteorology and air quality modeling in complex terrain for the benefit of those who wish to broaden their knowledge of the subject.

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AFFILIATION

Mr. DeMarrais is now retired. Mr. Clark, meteorologist in the Meteorology and Assessment Division, Environmental Sciences Research Laboratory, Environmental Research Center, Research Triangle Park, N.C. 27711, is on assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

SECTION 2

CATEGORIZED CHRONOLOGICAL LISTING OF STUDIES

Studies relating to specific topics are chronologically listed in the following tables. A brief summary is included in each listing, some of which appear in more than one table. The topics considered are as follows:

Table	Topic
1	Meteorological Phenomena Observed in Complex Terrain
2	Theories on Flow in Complex Terrain
3	Long-Range Transport in Complex Terrain
4	Windward Slope Phenomena
5	Leeward Slope Phenomena
6	Results of Field Studies-Meteorological Phenomena
7	Results of Field Studies-Transport and Diffusion
8	Models of Meteorological Phenomena
9	Models of Transport and Diffusion
10	Numerical, Statistical, and Computer Studies
11	Wind Tunnel, Water Channel, and Other Laboratory Experiments
12	Isolated Mountain Studies
13	Summary Reports

TABLE 1. METEOROLOGICAL PHENOMENA OBSERVED IN COMPLEX TERRAIN

Date	Author(s)	Contribution
1826	Daniell	Described the typical nocturnal, fair-weather, downslope movement of cold air in hilly terrain.
1840	Fornet	Described the typical diurnal variation of mountain and valley winds.
1914	Hesselberg & Sverdrup	Discussed how mountains influenced streamline flow and presented charts showing streamlines and isobars across the Alps.
1920	Young	Showed that a long uniform slope rising at a slight angle did not cause the same thermal variation and associated drainage wind as a steep slope.
1923	Cox	Found that downslope winds originated below the summit and that the size of the valley, the angle of slope, and the proximity of other slopes affected the downslope winds.
1924	Pollak	Observed that the mountain wind dissipated from above as well as from below (see Ayer, 1961, Whiteman and McKee, 1977).
1929	Baldit	Showed that airflow over mountain ranges had five parts: 1) discontinuity surface; 2) ascending current zone; 3) descending current zone; 4) abruptly changing atmospheric turbulence; and 5) undulations.
1931	Ekhart	Described in detail the time and space variations of wind speeds and directions in the vertical plane in an alpine valley.
1931	Althmanathan	Described how Poona, India, at the confluence of two rivers, was alternately affected by katabatic winds from the two river vallevs.

TABLE 1 (continued)

Date	Author(s)	Contribution
1932	Lange	Described the variation of temperature gradients and wind speeds in a valley.
1933	Heywood	Described katabatic flows in hilly terrain (see Conford 1938).
1934	Schell	Compared free-air temperatures (obtained via aircraft) over a valley with those at identical altitudes over the slopes of adjacent mountains.
1935	Moll	Reported on the variation of depth of both the upslope and downslope winds with distances along the slope.
1937a	Jelinek	Described in detail the diurnal variation of slope winds.
1937b	Jelinek	Correlated the vertical temperature gradients over the slopes and slope winds.
1938	Conford	Described katabatic flows on a 200-foot hill.
1940	Fons	Discussed the effects exerted by a forest in diverting winds and reducing their speeds.
1941	Hayes	Presented a comparison of temperatures and winds for six pairs of stations at identical elevations 50 m downslope on the north and south sides of a ridge which gradually rose in an eastward direction.
1944	Hewson & Gill	Reported on the first large-scale, field study documenting the meteorological conditions and transport and dispersion in a 50-mile long valley.
1945	US Army Air Force	Reported on the results of a large number of slow-ascent pilot balloon observations over the Los Angeles Basin and discussed the interactions of land and sea breezes with mountain and valley flows.
1945	Manley	Documented and described the flow of strong winds over a summit and the complicated flow in the valley on the downwind side.

TABLE 1 (continued)

Date	Author(s)	Contribution
1945	Hewson	Published a report on detailed meteorological observations along the 50-mile length of a valley (see Hewson & Gill 1943).
1946	Hewson	Described the meteorological considerations involved in evaluating radioactive air pollution problems at Hanford, Washington and Clinton, Tennessee.
1948	Neuberger	Reported that vegetation, acting as a filter, effectively removed gaseous and particulate matter (the green effect).
1949	White	Discussed the very large-scale effects of mountains on the transfer of momentum.
1949	Defant	Presented depictions of air flow over complex terrain which are often used as a basis for discussions of flow in complex terrain (a similar article entitled "Local Winds" by the same author appeared in the Compendium of Meteorology in 1951).
1949	Woelfe et al.	Reported that drainage winds did not move air into low-lying crevices and grottoes (sheltered areas have stagnant air).
1949	Hales	Reported that temperature lapse rates within a forest were typically the opposite of those in a cleared area (i.e., there were inversions in the area below the canopy in the daytime and lapse conditions at night).
1949	Shanks & Norris	Found the bottom of the katabatic flow layer bo be about one foot above the surface.
1950	Cross	Reported that katabatic winds were seldom detected at 40 feet above the surface of the slope.
1950	Smalley	Described unusual vertical currents observed over complex terrain south of San Francisco.
1952	Colson	Presented description of lee waves based on double theodolite observations made at Bishop, CA.

(continued)

TABLE 1 (continued)

Date	Author(s)	Contribution
1953	Holland	Presented a detailed summary of the meteorological parameters affecting dispersion in the mountainous area in and around Oak Ridge, TN.
1954	Radock	Described a procedure, using low-flying aircraft, for studying mountain effects on meteorological variables at low levels.
1954	Colson	Described work underway to improve the forecasting of the stand-wave in complex terrain.
1955	Stapley	Showed through the use of streamline analyses the marked spatial and temporal changes in surface air flow for airflow for a 30-mile by 30-mile area of a large valley.
1955 1	Meiklejohn	Reported that strong winds in the pass area were only 100 feet deep in an area where the valley depth was 1000 feet.
1957	Yoshino	Noted the different effects that the angle of slope on the leeside had on eddies formed in the lee of a summit.
1957	Dickson	Reported that katabatic winds were observed on practically every night that the pressure gradient was weak and the skies were clear.
1958	Thompson & Dickson	Found that the depth of nocturnal inversions slopes was generally above the top-most recording instrument (16 m).
1959	Buettner & Thyer	Concluded, in this first of a series of reports, that the length, height, steepness of sides of the valley, as well as well-defined distal and proximal ends, determined how well-developed a valley wind system could become.
1960	Thyer & Buettnes	Reported that the major area of air exchange between the slopes and the valley was at the ridge level area.
1960	Von Eschen	Described a nocturnal phenomenon whereby warm pulses of air interrupt the continuous cooling near the surface in the valley bottom.

(continued)

TABLE 1 (continued)

Date	Author(s)	Contribution
1961	Ayer	Reported that down-valley winds frequently dissipated from above (see Pollak, 1924 and Whiteman and McKee, 1977) and that inversions, which are shallower over the ridge top area, dissipate more rapidly than inversions over the lower parts of a valley.
1961	Sterten	Described the relationship of cloud conditions and mountain winds.
1961	Cramer & Lynott	Presented a cross-sectional analysis of potential temperature above a 50-mile stretch of complex terrain.
1961	Koch	Described the nocturnal thermal stratification in the valley and along the adjacent slopes.
1961	Schroeder	Described the anomalous phenomenon of downslope winds occurring in the daytime.
1962	Thyer & Buettner	Reported that the slope of the area between the winds in the valley bottom and the anti-winds aloft followed the slope of the valley floor and presented many figures showing the time and space variations of winds in the valley.
1962	Schultz	Reported the character of katabatic winds was pulsating with a depth of 40 to 50 feet.
1962	Baumgartner	Presented data on daily maximum and minimum temperatures at various heights above ground, at various altitudes and on various aspects along a slope in the Bavarian Forest.
1963	Sterten	Illustrated the diurnal vertical variation of winds in a valley.
1963	Davidson	Found that during stable conditic the area of maximum turbulence was near the ridgeline.
1963	Fuh	Discussed how the angle of the wind direction relative to the orientation of the valley affected wind speed.

(continued)

TABLE 1 (continued)

Date	Author(s)	Contribution
1963	Petrosiants & Chanysheva	Discussed the effects of dimensions and orientations of valleys on mountain-valley circulations.
1963	Davidson & Fau	Described the variation of wind speed with height over the valley center.
1963	Tanner	Presented the results of a statistical study of the variations of temperature with respect to elevation in a moist and a dry mountain regime.
1964	Buettner et al.	Discovered that the depth of the katabatic flow was usually less than 20 feet.
1965	Buettner & Thyer	Illustrated the diurnal variations of mountain, valley, and anti-winds and noted that valley and upslope winds were initiated simultaneously.
1965	Cummings et al.	Based on a three-year study in complex terrain around a power plant, concluded that plume impaction on nearby high terrain was not a problem.
1965	Kasai	Used time-lapse photography to show that cloud formation was associated with mountain waves.
1965	Geiger	Presented tables defining insolation as a function of time of year, latitude, orientation of valley, and inclination of slope.
1965	Smith	Discovered from tracer studies that plumes impacted lee sides far below the summit.
1967	Martin & Barber	Detected the plume from a 137-m stack at the surface 1 km downwind.
1967	Lopez	Described daytime downslope winds on the east side of the Andes Mountains.
1967	Thompson	Described the thermal circulation over a small side of a major range.
1968	Tyson	Reported that the thermally-produced mountain-valley wind was able to support eddy energy in the range between convective and mechanical turbulence.

(continued)

TABLE 1 (continued)

Date	Author(s)	Contribution
1968	MacHattie	Discovered that cross-valley components of the wind showed a more pronounced diurnal cycle than components along the valley.
1968	DeMarrais et al.	Reported on vertical temperature profiles observed along the main and several tributary drainages of a large valley.
1969	Burov	Described a technique for studying diffusion around a 100-m hill by means of stereophotos.
1972	Miller	Obtained vertical soundings of temperatures, and oxidant pollution over complex terrain.
1972	Schiermeier	Described the downwash problem near a power plant located downwind of a ridge.
1971	Dames & Moore et al.	Based on consideration of local winds, terrain effects, and professional judgment, authors concluded that the Colorado Plateau region could be divided into separate air sheds and that there be little significant meteorological interaction between these air sheds during stagnation conditions (see Van der Hoven et al., 1972).
1972	Van der Hoven et al.	Discussed the potential for pollution problems in the southwestern United States and concluded that power plant plume impaction on terrain at same altitude as plume could constitute a problem (see Dames and Moore et al., 1971).
1972	Tyson & Preston-White	Demonstrated that large-scale topographically-induced mountain-plain and plain-mountain winds existed above the mountain, valley, and anti-winds of the valley (that is, there were three layers of winds in addition to winds at the gradient level).
1973	Start et al.	Discussed three mechanisms which appeared to enhance mechanical turbulence in complex terrain.
1973	Edinger	Explained how urban plumes eventually impacted slopes in complex terrain.

(continued)

TABLE 1 (continued)

Date	Author(s)	Contribution
1973	Leahey & Halitsky	Used a turbulence climatology and Pasquill stability classes to make quantitative estimates of diffusion at a Hudson River Valley location.
1973	Hindman	Determined the flow of air currents in complex terrain from observations of the breakup of clouds.
1974	Leahey & Rowe	Derived diffusion coefficients from wind data over a mountain valley, a long two-dimensional ridge, and a river bank and discovered that the airflow was very different for each of the topographic features.
1974	Kao et al.	Showed how wind streamline patterns (based on data from 15 sites) changed throughout the day in a large valley.
1974	Egami et al.	Showed that mountain-valley winds and anti-winds aloft occurred in the area of the Mohave Power Plant.
1974	Hovind et al.	Reported results from field studies at three separate sites in the southwestern United States to illustrate the effect of terrain roughness upon plume dispersion.
1974	MacCready et al.	Discovered, contrary to normal assumption, that with weak katabatic flows and thermal stability, turbulence existed.
1974	Start et al.	Discovered that dispersion estimates in accord with Pasquill stability classifications underestimated dilution by a factor of 4 to 15 in complex terrain.
1974	Giroux et al.	Discovered, by observing power plant plume dispersion, that there was no buildup in concentrations due to the diurnal back-and-forth movement of air.
1975	Air Monitoring Center, Rockwell, Int.	Determined from extensive field investigations in the area of the Navaho Generating Station that the highest SO_2 concentrations impacted on high terrain downwind of the source.

(continued)

TABLE 1 (continued)

Date	Author(s)	Contribution
1976	Start et al.	Discovered that: 1) elevated plume centerline concentrations measured over rough terrain averaged two to four times more dilution than that predicted for smooth terrain and 2) the physical setting and topography of a particular site had a considerable effect on the dilution in complex terrain.
1976	Williams & Cudney	Concluded from aircraft observations that there was direct plume impaction on high terrain downwind of a power plant.
1976	Roffman et al.	Reported that the results of a field study showed that models used by regulatory agencies (see Burt, 1977; Van der Hoven et al., 1972) overpredicted concentrations by a factor of 8.7 on the average.
1976	Clements & Barr	Discovered that slope wind speeds were typically 1 to 2 mps and that a major part of the air exchange in a valley occurs near the ridgeline.
1976	Paegle & Paegle	Determined the frequency spectra of atmospheric motions in the vicinity of a mountain barrier.
1976	Davis et al.	Reported that the green effect (see Newberger, 1948) could reduce the concentrations of small-sized aerosols by 50% in complex terrain.
1976	Weier et al.	Showed that plume opacity varied as much as 14 to 87% depending only on geographic location of the source and time of day.
1976	Wilson et al.	Discovered from dispersion studies that for low speeds vertical mixing was enhanced to almost the same degree as horizontal dispersion was by the meander.
1977	Whaley & Lee	Discovered enhanced lateral mixing of plumes in complex terrain.
1977	Chung	Discussed the influence of large-scale mountains on airflow and lee cyclogensis.

(continued)

TABLE 1 (continued)

Date	Author(s)	Contribution
1977	Kao & Taylor	Discovered marked lateral spread aloft over complex terrain despite the fact that thermal stability was observed.
1977	Nappo	Discovered, after analyzing surface and winds-aloft data, little horizontal variability of winds on a scale of 100 km during unstable conditions and great horizontal variability during stable conditions.
1977	Benjamin et al.	Reported that high concentrations impacted on elevated terrain during stable conditions.
1977	Whiteman & McKee	Reported that the inversion top was observed to lower with time on a clear morning (see Pollak, 1924; Ayer, 1961).
1978	Lilly	Described the turbulence and vertical motions associated with a major downslope windstorm.
1978	Smith	Determined that the drag on the airflow moving across the Blue Ridge Mountains near Harpers Ferry, WV caused an average pressure difference of 0.5 mb across the ridge.
1978	Barry	Reviewed the contributions of Horace Benedict de Saussure who late in the 18th century determined that in the daytime, the air over valleys was cooler than that at the same altitude over the mountain slopes.
1979	Steffen et al.	Concluded that the winds at the ridge top appeared to be driven by meso- or synoptic-scale forces, while the flow in the valleys was influenced mostly by terrain discontinuities and inhomogeneities in surface heating.
1979	Banta & Cotton	Observed that each afternoon the emergence of clean, dry air and gusty winds served to flush pollutants out of a valley.

(continued)

TABLE 1 (continued)

Date	Author(s)	Contribution
1979	Whaley & Gainer	Discussed the behavior of buoyant, merging plumes from two natural-gas sulfur extraction plants in the foothills of the Canadian Rocky Mountains.
1979	Norton & Roffman	Studied data from two airports in the Pittsburgh area and concluded that the airport winds represented mesoscale flow but not the flow in the valleys in the area.
1980	Bradley	Measured the turbulent wind structure for neutral conditions using a 100-m tower at the crest of a 170-m hill.

TABLE 2. THEORIES ON FLOW IN COMPLEX TERRAIN

Date	Author(s)	Contribution
1866	Hann	Concluded that there was a release of latent heat on the windward side and adiabatic warming on the leeward side of the mountain during descent.
1870	Berger	Presented hypothesis on the causes of mountain and valley flows.
1910	Defant	Hypothesized that pressure gradients were primarily responsible for fair weather mountain-valley flows (see Defant, 1949).
1918	Newnham	Hypothesized that it was the difference of temperature between the air near the ground on the slopes and the free air that initially caused a valley wind.
1919	Hann	Concluded that the valley wind system resulted from the inclination of constant pressure surfaces.
1923	Wegner	Explained the mountain-valley flow using the circulation theorem of Bjerknes.
1932	Ekman	Discussed the dynamics of wind flow in mountainous terrain using ideas and data from Hesselberg and Sverdrup (1914).
1938	Wagner	Presented a theory and compared his results to field observations (see Defant, 1949).
1938	Ekhart	Presented a comprehensive comparison of many theories including those of Hann, 1919; Wegner, 1923; Wagner, 1938; and Ekhart, 1938.
1943	Lyra	Derived an equation for the lee wave - this work is considered the beginning of lee wave theory (see Merbt, 1959).

(continued)

TABLE 2 (continued)

Date	Author(s)	Contribution
1947	Queney	Discussed the use of the perturbation theory to explain the flow in mountainous terrain.
1947b	Sutton	Discussed the theoretical distribution of airborne pollution from factory chimneys. (The suggested method for calculating downwind dispersion in this report was used in complex terrain for many years.)
1949	Scorer	Presented a lee wave theory valid for streamline, dry, isentropic, inviscid flow in which the disturbance is only a small portion of the wind velocity.
1949	Defant	Summarized the current knowledge of theories of airflow in complex terrain.
1953	Gleeson	Derived expressions for the horizontal components of the valley wind as functions of the slope of the floor, turbulent heat conduction, and turbulent friction.
1953	Scorer	Discussed the theory of lee waves and the difficulties in developing a model of the flow downstream of the ridge.
1955a	Scorer	Presented a very detailed mathematical explanation of the lee wave.
1955b	Scorer	Discussed eddies on the windward as well as leeward side of the mountains.
1956	Scorer	Discussed the perturbation theory with reference to the flow around an isolated hill.
1956	Corby & Wallington	Discussed lee waves over the British Isles.
1956	Corby & Sawyer	Discussed the effects of an upper boundary and high level conditions on the airflow over a ridge.

(continued)

TABLE 2 (continued)

Date	Author(s)	Contribution
1959	Merbt	Discussed the solution of the two-dimensional lee-wave equation for arbitrary mountain profiles.
1960	Doos	Discussed a mountain-wave theory which included the effect of the vertical variation of wind and stability.
1962	Thyer & Buettner	Presented Thyer's theory of valley winds.
1962	Musaelyan	Presented a detailed theoretical discussion of the vertical currents generated by a barrier.
1966	Thyer	Developed and evaluated a numerical model using extensive field data that featured valley and slope winds, anti-winds, and vertical currents.
1966	Khalkechev	Concluded that the Coriolis force had a negligible effect on winds in a narrow valley but had to be considered in a wide valley.
1973	Fraser et al.	Presented a model emphasizing the dynamic effects of airflow moving over a barrier.
1975	Klemp & Lilly	Derived a theory for the dynamics of strong surface winds on the lee side of a large mountain and compared the theoretical results with observations.
1975	Drazin & Su	Derived a method for calculating the flow involved in a lee eddy.
1976	Blumen & McGregor	Presented a theoretical study of lee waves formed by an isolated hill.
1976	Tang	Presented the results of a theoretical study of cross-valley circulation.
1979	Issacs et al.	Discussed an application of potential flow theory to a Gaussian source diffusion model in complex terrain.

(continued)

TABLE 2 (continued)

Date	Author(s)	Contribution
1979	Mason & Sykes	Compared the theoretical results in airflow over a ridge with observations of airflow over a 130-m hill.

TABLE 3. LONG RANGE TRANSPORT IN COMPLEX TERRAIN

Date	Author(s)	Contribution
1943	Hewson & Gill	Reported on the first large-scale study documenting the meteorology, transport, and dispersion in a 50-mile long valley.
1945	Hewson	Reported on the transport of air pollution out to a distance of 50 miles in the Columbia River Valley (see Hewson & Gill, 1943).
1952	Braham et al.	Tracked a plume 107 miles over mountainous terrain in New Mexico.
1959	Kassander	Described a tracer study of airflow 20 miles over mountainous terrain.
1970	Edinger	Described how urban plumes impacted on the mountain sides downwind of the Los Angeles basin.
1970	Brodine et al.	Hypothesized how a toxic gas release in complex terrain resulted in the killing of sheep many km away from the release point.
1971	Stephens & McCaldin	Determined the half-life of SO_2 and pollutant concentrations in plumes from power plants to a distance of 80 km.
1974	Giroux et al.	Measured ground-level traces of a power plant plume 40 km from the source in a large valley; the plume's primary impact occurred 25 km from the source.

TABLE 4. WINDWARD SLOPE PHENOMENA

Date	Author(s)	Contribution
1866	Hann	Concluded there was a release of latent heat as air ascended on the windward side of a mountain.
1955b	Scorer	Discussed eddies on the windward and lee sides of mountains.
1962	Myers	Developed a model of the two dimensional laminar flow on the windward side of a ridge.
1968	Orville	Discussed the wave produced on the upwind side of the mountain by the damming of the airflow.
1970	Edinger	Described how urban plumes impacted on the mountain side downwind of the Los Angeles basin.
1970	Long	Used two different density fluids to show the upstream effect of an obstacle (in a water channel).
1977	Kitabayaski	Conducted a wind tunnel and a field study of airflow upstream of a ridge.
1977	Furukawa	Used numerical experiments and showed how mountain affected the airflow on the windward side of the ridge.

TABLE 5. LEEWARD SLOPE PHENOMENA

Date	Author(s)	Contribution
1866	Hann	Concluded that there was adibatic warming of air on the leeward side of the mountain during descent.
1943	Lyra	Derived an equation for the lee wave (see Merbt, 1959).
1945	Manley	Documented and described the flow of strong winds over a summit and the complicated flow on the lee side.
1949	Scorer	Presented a theory on the waves in the lee of mountains.
1952	Colson	Presented several examples of standing-wave patterns based on double-theodolite observations made at Bishop, CA.
1953	Long	Described a water channel simulation of the lee wave phenomenon observed at Bishop, CA.
1953	Scorer	Discussed the theory of lee waves and listed the difficulties involved in modeling lee waves.
1954	Corby	Reviewed most of the major works dealing with flows over and downwind of mountain ridges.
1954	Colson	Described work being done to improve the forecasting of the standing wave in mountainous terrain.
1955a	Scorer	Presented a very detailed mathematical explanation of the variation with height of the wave and the amplitude of lee waves.

(continued)

TABLE 5 (continued)

Date	Author(s)	Contribution
1955	Long	Presented a trilogy on the flow of stratified fluids over and around an isolated object.
1955	Forchtgott	Discussed the results of extensive field observations of the lee wave over mountains of western Europe.
1955b	Scorer & Wallington	Discussed lee waves formed over the mountains of the British Isles.
1956	Scorer & Wilkinson	Discussed the lee pattern produced by an isolated hill.
1957	Yoshino	Noted the different effects that the angle of slope on the lee side had on eddies formed in the lee of a summit.
1957	Wuertele	Presented a three-dimensional model of the eddy formed downwind of an isolated mountain.
1958	Corby & Sawyer	Discussed the effects of an upper boundary and high-level conditions on the airflow over mountains.
1959	Merbt	Discussed the effect of the ridge shape on the lee eddy.
1960	Queney et al.	Reviewed the literature on lee-wave phenomena (see Nicholls, 1973).
1960	Sinha	Described the semi-permanent standing waves observed over Kabul, Afghanistan.
1962	Musaelyan	Discussed the vortex developments downwind of a ridgeline.
1963	Davidson	Described the airflow on the lee slopes of a small valley.
1964	Buettner et al.	Discovered that tracer material released on the lee side of a summit showed that particles with appreciable settling velocities were pressed onto the slope while particles of 10 microns or less were carried aloft.

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TABLE 5 (continued)

Date	Author(s)	Contribution
1965	Kusai	Used time-lapse photography to show cloud formations associated with mountain waves.
1965	Smith	Discovered from tracer studies that plumes impacted on lee sides far below the summit.
1967	Lopez	Described daytime downslope winds on the east side of the Andes Mountains.
1973	Nicholls	Updated the review of the literature on lee-wave phenomena (see Queney et al., 1960).
1974	Manabe & Terpstra	Concluded from a numerical experiment that the probability of cyclogenesis increased significantly on the lee side of major mountain ranges where the core of the westerly jet was located.
1975	Klemp & Lilly	Derived a theory for the dynamics of strong surface winds on the lee side of a mountain range and compared the theoretical results with observations.
1975	Drazin & Su	Derived a method for calculating the flow in a lee eddy.
1976	Smith	Studied lee waves in the Blue Ridge Mountains.
1976	Blumen & McGregor	Presented a theoretical study of lee waves formed by an isolated hill.
1977	Chung	Discussed the influence of large-scale mountains on air flow and lee cyclogenesis.
1977	Furukawa	Used numerical experiments to determine the airflow on the lee side of a ridge.
1978	Lilly	Described the turbulence and vertical motions associated with a major downslope windstorm.
1979	Arya & Shipman	Studied via a wind tunnel the separate bubble formed on the lee side of a ridge.

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TABLE 5 (continued)

Date	Author(s)	Contribution
1979	Inoue	Reported on the resonance of lee waves of a stratified flow over two barriers.

ABSTRACT

Modeling air quality in complex terrain has been and remains to be a difficult task simply because of the difficulty in parameterizing the complex wind flow regimes. Due to the complex terrain, significant submesoscale forces are established to perturb the mesoscale wind field. These forces must first be better understood and the algorithms must be developed to adequately simulate the effects of these forces before one can hope to reasonably model air quality in complex terrain. This literature review summarizes over 250 studies of meteorology and air quality modeling in complex terrain for the benefit of those who wish to broaden their knowledge of the subject.

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SECTION 1

INTRODUCTION

The concern for air quality in valleys and the effects of plume impaction on mountain slopes in the Appalachian Mountains and in the western United States created the need for accurate air quality simulation models applicable to complex terrain to 1) assess environmental impacts of proposed plants and 2) predict the likelihood of violating environmental regulations near proposed or existing plants assuming various emission and meteorological scenarios. The process of developing accurate air quality simulation models for complex terrain has been slow because meteorological variables are greatly influenced by complex factors that are difficult to model adequately. One must understand the effects of terrain on the meteorological variables before it is possible to accurately model the air quality.

As an aid to a better understanding of terrain effects on meteorological variables in complex terrain, this literature review provides a historical perspective, an extensive bibliography of over 250 studies with a brief description of each study of meteorology and air quality modeling in complex terrain. For the convenience of the user, brief descriptions of these studies are categorized and listed chronologically in 13 tables according to topic (Section 2). Some of these listings occur in more than one table since they relate to more than one topic. In addition, an uncategorized, chronological listing of references accompanied by a short description of the study is included (Section 3). This reference list is by no means complete. The blank pages at the end of this section are provided for the user to add references he considers pertinent.

TABLE 6. RESULTS OF FIELD STUDIES--METEOROLOGICAL PHENOMENA

Date	Author(s)	Contribution
1923	Cox	Conducted studies in several valleys in western North Carolina for several years investigating temperature variations and the fine structure of winds.
1927	Koschmieder	Used balloons, kites, and gliders to study the three-dimensional flow around a hill.
1931	Ekhart	Summarized the results of an investigation of temporal and spatial variation of winds in the vertical over an alpine valley.
1932	Lange	Investigated the variation of temperature gradients and wind speeds in complex terrain.
1933	Heywood	Reported on a detailed study of katabatic winds in hilly terrain in England (see Conford, 1938).
1934	Schell	Compared free-air temperatures over a valley with those at identical altitudes over the slopes of adjacent mountains.
1935	Moll	Reported on the variation along the slope of upslope and downslope winds.
1937a	Jelinek	Reported on a study of the diurnal variation of slope winds.
1937b	Jelinek	Described a study of the correlation of vertical temperature gradients over the slope and slope winds.
1938	Conford	Described a study of katabatic winds on a 200-foot hill.

(continued)

TABLE 6 (continued)

Date	Author(s)	Contribution
1943	Hewson & Gill	Reported on the first large-scale study to document the meteorological conditions and transport and dispersion in a 50-mile long valley.
1945	U.S. Army Air Force	Summarized the results of a large number of slow-ascent pilot balloon observations over the Los Angeles Basin.
1945	Johnstone et al.	Reported on the practical methods for grounding aerosols to selected targets in complex terrain.
1945	Manley	Documented and described the flow of strong winds over a summit and the flow on the lee side.
1945	Hewson	Published a report on the variation of temperatures and winds along 50 miles of the Columbia River Valley (see Hewson and Gill, 1943).
1946	Hewson	Reported that investigators were unable to detect katabatic winds at a height of 10 m above the slopes (i.e., katabatic winds were shallow).
1953	Holland	Presented a detailed summary of the meteorological parameters affecting dispersion in the mountainous area in and around Oak Ridge, TN.
1955	Forchtgott	Discussed results of extensive field observations of the lee wave over mountains of western Europe.
1957	Dickson	Discussed climatology of diurnal inversions in the Jordan Valley (Utah).
1958	Thompson & Dickson	Discovered after studying the depths of nocturnal inversions on slopes that their tops were generally above the top-most recording instrument (16 m).

(continued)

TABLE 6 (continued)

Date	Author(s)	Contribution
1959	Buettner & Thyer	Concluded, in this first of a series of reports, that the length, height, steepness of sides of the valley, as well as well-developed distal and proximal ends determined how well-developed a valley wind system could become.
1960	Thyer & Buettner	Presented detailed documentation of the winds in the vertical for selected locations across individual valleys (unique investigations.
1960	Von Eschen	Described pulses of warm air which temporarily interrupt the continuous nocturnal cooling in a valley bottom.
1961	Sterten	Described in detail the relationship between cloud cover and mountain winds.
1962	Thyer & Buettner	Presented numerous diagrams showing the time and space variations of winds in a valley.
1963	Sterten	Presented detailed figures on the diurnal variation of the wind profiles in a valley.
1963	Fuh	Discussed how the angle of the wind direction relative to the orientation of the valley affected wind speed.
1963	Petrosiants & Chanysheva	Discussed the effects of dimensions and orientations of valleys on mountain-valley circulations.
1963	Davidson & Rao	Described the variation of wind speed with height over the valley center.
1963	Tanner	Presented the results of a statistical study of the temperature variations with height along the slopes of a moist and a dry mountain regime.
1967	Thompson	Described the thermal circulation of a small side canyon of a major range.

TABLE 6 (continued)

Date	Author(s)	Contribution
1968	Tyson	Discovered that the thermally-produced mountain valley wind was able to support eddy energy in the range between convection and mechanical turbulence.
1968	MacHattie	Discovered that the cross-valley component of the wind showed a more pronounced diurnal cycle than the components along the valley.
1968	DeMarrais et al.	Reported on vertical temperature profiles observed along the main and several tributary drainages of a large valley.
1972	Miller et al.	Obtained vertical soundings of temperatures, winds, and oxidant pollution over complex terrain.
1974	Egami et al.	Showed that mountain-valley winds and anti-winds aloft occurred in the area of the Mohave power plant.
1976	Clements & Barr	Discovered that slope winds were typically 1 to 2 mps and that a major part of the air exchange in a valley occurred near the ridge line.
1976	Paegle & Paegle	Determined the frequency spectra of atmospheric motions in the vicinity of a mountain barrier.
1976	Smith	Studied lee waves in the Blue Ridge Mountains.
1976	Weir	Showed that plume opacity varied as much as 14 to 87% depending only on geographic location of the source and time of day.
1979	Steffen	Found that the winds at the ridge top appeared to be driven by meso- or synoptic-scale forces while the flow in the valleys was mostly influenced by terrain discontinuities and inhomogeneities in surface heating.
1979	Mason & Sykes	Compared theoretical results on airflow over a ridge with observations of airflow over a 130-m hill.

TABLE 7. RESULTS OF FIELD STUDIES--TRANSPORT AND DISPERSION

Date	Author(s)	Contribution
1943	Hewson & Gill	Reported on the first large-scale study documenting the meteorological conditions and transport and dispersion in a 50-mile long valley.
1945	Johnstone	Reported on the practical methods for getting aerosols to targets on the ground in complex terrain.
1945	Hewson	Published a report on the transport and dispersion of the emissions from a large smelter in the Columbia River Valley in southern Canada (see Hewson and Gill, 1943).
1947a	Sutton	Discussed in detail the development of approximate formulae for point and line source derived by statistical analysis of large amounts of field data. (Eventually these formulae were used in complex terrain applications for many years.)
1947b	Sutton	Compared results from diffusion formulae to pollution concentrations downwind of a large point source in complex terrain.
1949	Schrenk et al.	Described in detail the wind flows typical of the stagnation associated with the Donora, Pennsylvania air pollution disaster which occurred in complex terrain.
1959	Kassander	Discovered that a plume moving over mountainous terrain for more than 20 miles spread more in the horizontal than had been expected based on cloud-seeding results.
1962	Lawrence	Developed a formula for use in constructing surface pollution profiles in a rural hilly area surrounded by distant industrial sources.

(continued)

TABLE 7 (continued)

Date	Author(s)	Contribution
1964	Buettner et al.	Discovered that tracer material released from the lee slope showed that particles with appreciable settling velocities were deposited onto the slope while particles of 10 microns and smaller were carried aloft.
1965	Cummings et al.	Based on a three-year study in complex terrain around a power plant concluded that plume impaction on nearby high terrain was not a problem.
1965	Smith	Discovered from tracer studies that plumes impacted on the lee slopes far below the summit.
1967	Martin & Barber	Detected a plume on the ground from a 137-m stack one km downwind.
1969	Burov et al.	Described a technique for studying diffusion around a 100-m hill by means of sterophotos.
1970	Edinger et al.	Explained how urban plumes impacted on the mountain side downwind of the Los Angeles basin.
1970	National Air Pollution Control Administration	Showed the spatial distribution of several pollutants over an urban area in complex terrain.
1970	Hinds	Reported that flat land diffusion calculations typically overestimated the concentrations in complex terrain by a factor of two.
1970	Brodine et al.	Hypothesized how a toxic gas release in complex terrain resulted in the killing of sheep many km away from the release point.
1971	Stephens & McCaldin	Determined half-life of SO_2 and pollutant concentrations in plumes from power plants out to a distance of 80 km.
1971	Carpenter et al.	Summarized 20 years of detailed documentation of dispersion in complex terrain.

(continued)

TABLE 7 (continued)

Date	Author(s)	Contribution
1971	U.S. Environmental Protection Agency	Discussed the results of investigations of two air pollution problems in complex terrain.
1971	Dames & Moore et al.	Based on consideration of local winds, terrain effects and professional judgment, authors concluded that the Colorado Plateau region could be divided into separate air sheds and that there would be little significant meteorological interaction between these sheds during stagnation conditions (see Van der Hoven et al., 1972).
1972	Schiermeier	Described the downwash problem created at a power plant located downwind of a ridge.
1972	Van der Hoven et al.	Discussed the potential for pollution problems in the southwestern United States and concluded that power plant plume impaction on high terrain at the same altitude as the plume could constitute a problem (see Dames and Moore et al., 1971).
1972	Tyson & Preston-Whyte	Demonstrated that large-scale topographically-induced mountain-plain and plain-mountain winds existed above the mountain, valley, and anti-winds of the valley (that is, there were three layers of winds in addition to winds at the gradient level).
1973	Start et al.	Discussed the three mechanisms which appeared to enhance mechanical turbulence in complex terrain.
1973	Edinger	Explained how an urban plume eventually impacted slopes in complex terrain.
1973	Leahey & Halitsky	Used a turbulence climatology and Pasquill stability classes to make quantitative estimates of diffusion at a Hudson River Valley location.
1973	Leslie & Smith	Explored numerically the effectiveness of katabatic winds in dispersing pollutants and compared the results to field data.

(continued)

TABLE 7 (continued)

Date	Author(s)	Contribution
1974	Leahey & Rowe	Reported that the Pasquill classification system yielded values that underestimated dispersion in complex terrain.
1974	Kao et al.	Showed how streamline patterns based on the data from 15 sites changed throughout the day in a large valley.
1974	Egami et al.	Found that the polluted air over a valley could have two peak concentrations: one for recent releases and the other from aged material.
1974	Hovind et al.	Found that the method for estimating dispersion in smooth terrain underestimated dispersion at a canyon area by a factor of 10.
1974	MacCready et al.	Discovered, contrary to the normal assumption, that with weak, katabatic flows and thermal stability, turbulence existed.
1974	Start et al.	Found that dispersion estimates in accord with Pasquill stability classifications underestimated dilution by a factor of 4 to 15 in complex terrain.
1974	Giroux et al.	Discovered, after tracking a power plant plume across a large valley, there were no significant differences between concentrations measured in elevated terrain directly in the plume path and the surrounding flatlands.
1975	Air Monitoring Center, Rockwell International	Determined from an extensive field investigation in the area of the Navaho Generating Station that the highest SO_2 concentrations impacted high terrain downwind of the source.
1976	Start et al.	Discovered that: 1) elevated plume centerline concentrations measured over rough terrain averaged two to four times more dilution than that predicted for smooth terrain and 2) the physical setting and topography of a particular site had a considerable effect on the dilution in complex terrain.

(continued)

TABLE 7 (continued)

Date	Author(s)	Contribution
1976	Roffman et al.	Reported that the results of a field study showed models used by regulatory agencies (see Burt, 1977; Van der Hoven et al., 1972) overpredicted concentrations by a factor of 8.7 on average.
1976	Lanta et al.	Reported that diffusion data from three areas indicated that the INTERA model was more accurate than the NOAA (see Van der Hoven et al., 1972) and EPA (see Burt, 1977) models.
1976	Wilson et al.	Discovered from dispersion studies that for low wind speeds, vertical mixing was enhanced to almost the same degree as horizontal dispersion was by the meander.
1977	Whaley & Lee	Discovered enhanced lateral mixing of plumes in complex terrain.
1977	Fabrick et al.	Compared Gaussian and grid-type models and concluded, "After careful review of the Gaussian evaluation tests, one reaches the conclusion that almost any desired result can be obtained given the range of options for the dispersion parameters, plume trajectory in complex terrain, etc. and the range of uncertainty in the observed wind speed, wind direction, and atmospheric stability."
1977	Kao & Taylor	Discovered marked lateral plume spreading over complex terrain in spite of the fact that thermal stability was indicated.
1977	Nappo	Discovered, after analyzing surface and winds-aloft data, minimal horizontal variability of winds on a scale of 100 km during unstable conditions and great horizontal variability during stable conditions.
1977	Hovind et al.	Discovered that the highest surface concentrations in a 5-to-10-km wide valley occurred with cross-valley flow and daytime fumigation.

(continued)

TABLE 7 (continued)

Date	Author(s)	Contribution
1979	Graham et al.	Used field data and wind tunnel tests to demonstrate that high terrain upwind of a power plant stack restricted plume rise while it increased vertical spreading.
1979	Spangler et al.	Used four years of data from a network of stations in the Huntington Canyon area to conclude that SO_2 standards were not violated.
1979	Ruff	Presented evidence of the small-scale movement of air in a geothermal area in complex terrain.
1979	Banta & Cotton	Described in detail the diurnal flow patterns over a flat plateau surrounded by mountains.
1979	Minott & Shearer	Investigated diffusion in deep U-shaped valleys and found that vertical dispersion rates in the valleys were similar to those over flat land with similar surface roughness.
1979	Wan	Concluded from 571 observations collected over two years in the Hudson River Valley that thermal and topographic effects appear to increase the diffusion rates over complex terrain (compared to results over flat terrain).
1979	Koch et al.	Described a large-scale field study conducted in Virginia.
1979	Whaley & Gainer	Discussed the behavior of buoyant, merging plumes from two natural gas, sulfur extraction plants in the foothills of the Canadian Rocky Mountains.
1979	Norton & Ruffman	Studied data from two airports in the Pittsburgh area and concluded that the airport winds represented mesoscale flow but not the flow of the valleys in the area.
1979	Chan	Descovered that the plumes from a power plant followed the contour of the ground beneath it.

(continued)

TABLE 7 (continued)

Date	Author(s)	Contribution
1980	Bradley	Measured the turbulent wind structure for neutral conditions using a 100-m tower at the crest of a 170-m hill.
1980	Pickering et al.	Provided a large data base from a field study in complex terrain.

TABLE 8. MODELS OF METEOROLOGICAL PHENOMENA

Date	Author(s)	Contribution
1953	Gleeson	Derived a model for determining the horizontal components of the valley wind in the mid-valley.
1953	Scorer	Discussed the theory of lee waves and the practical problems in developing a model of the flow downstream of a ridge.
1957	Wurtele	Presented a three-dimensional model of the eddy produced downwind of an isolated mountain.
1962	Thyer & Buettner	Presented Thyer's valley wind theory.
1962	Myers	Developed a model of the two-dimensional laminar wind flow on the windward side of a ridge.
1966	Thyer	Produced a numerical model that featured valley and slope winds, anti-winds, and vertical currents using extensive field data for development and verification.
1966	Holton	Derived equations for simulating the dynamics involved in wind oscillations over sloping terrain.
1966	Khalkechev	Discovered that the Coriolis force had a negligible effect on the winds in a narrow valley, but had to be considered in a wide valley.
1969	Goltsberg (editor)	Described the use of morphometric indices for graphically describing complex terrain (not a model of meteorological phenomena, but a description of the structure of the terrain which, in turn, affects flow).

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TABLE 8 (continued)

Date	Author(s)	Contribution
1971	Petkovsek & Hocevar	Presented a simple model of nocturnal drainage flow.
1975	Mahrer & Pielke	Presented results of the application of a two-dimensional, numerical model of airflow over a mountain.
1977	Yocke & Liu	Developed a three-dimensional model for the prediction of wind fields over rugged terrain.
1979	Mason & Sykes	Presented a simple Cartesian model of boundary layer flow over topography.

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TABLE 9. MODELS OF TRANSPORT AND DIFFUSION

Date	Author(s)	Contribution
1947a	Sutton	Discussed in detail the development of approximate formulae for point and line source derived by a statistical analysis of field data.
1947b	Sutton	Discussed the results of a comparison of observed concentrations and calculated concentrations based on diffusion formulae.
1957	Wurtele	Presented a three-dimensional model of the eddy produced downwind of an isolated mountain.
1962	Lawrence	Developed a formula for use in constructing pollution profiles in a rural hilly area surrounded by distant industrial sources.
1970	Cramer et al.	Described a computerized multi-source model for use in complex terrain.
1970	Reiquam	Developed a mathematical model for a large valley in complex terrain.
1971	Carpenter et al.	Discussed the plume dispersion models used at the Tennessee Valley Authority power plants.
1972	Van der Hoven et al.	Presented a model which called for power plant plume impaction on downwind terrain at the same elevation as the plume. (The model became known as the NOAA model.)
1973	Fraser et al.	Presented a theoretical model emphasizing the dynamic effects of airflow over a barrier.
1973	Kozhevnikov	Presented one linear and two non-linear models to describe the flow around a mountain.

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TABLE 9 (continued)

Date	Author(s)	Contribution
1973	Walden Research	Presented the results of an application of the EPA Valley Model in 51 Air Quality Control Regions (see Burt, 1977).
1974	Ruffman & Grimble	Developed a model which accounted for terrain features, variations in wind and diffusivity profiles, and mixing depth.
1975	Intercomp Resources Development	Claimed the EPA (see Burt, 1979) and NOAA (see Van der Hoven, 1972) models predicted higher concentrations than those which were observed, while the Intercomp model was the most accurate.
1975	Seinfeld	Described two- and three-dimensional dispersion equations for predicting plume concentrations in complex terrain.
1976	Roffman et al.	Reported that the results of a field study showed the models used by regulatory agencies (see Burt, 1977; Van der Hoven et al., 1972) overpredicted concentrations by a factor of 8.7 on the average.
1976	Bowers et al.	Reported that the measurements of the characteristics of power plant plumes indicated that their group developed a good short-term model.
1976	Fox et al.	Developed a geeralized predictive model for air quality in complex terrain.
1976	Lantz et al.	Reported that diffusion data from three areas indicated that the INTERA model was more accurate than the NOAA (see Van der Hoven et al., 1972) and EPA (see Burt, 1977) models.
1976	Egan & Bass	Reviewed air quality modeling in complex terrain.
1976	Kao	Constructed a model for turbulent diffusion over complex terrain.
1977	Koch et al.	Used the results from 16 independent field investigations to evaluate complex terrain models.

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TABLE 9 (continued)

Date	Author(s)	Contribution
1977	Haussling	Used a numerical technique and a model to demonstrate the transition of a viscous flow over an infinitely long barrier from homogeneous to stably stratified conditions.
1977	Fabrick et al.	Compared Gaussian and grid-type models and concluded, "After careful review of the Gaussian evaluation tests, one reaches the conclusion that almost any desired result can be obtained given the range of options for the dispersion parameters, plume trajectory in complex terrain, etc., and the range of uncertainty in the observed wind speed, wind direction, and atmospheric stability."
1977	Swolik et al.	Proposed a complex terrain model based on the data from Large Power Plant Effluent Study (LAPPES) (see Schiermeier, 1972).
1977	Cabe et al.	Reported success, particularly when concentrations were high, with a complex terrain model that assumed impaction on high terrain.
1977	Elliott et al.	Proposed changes for the Gaussian plume dispersion models after examining the results of 13 field tests and finding the smooth terrain model overpredicted the concentrations.
1977	Huffnagle	Concluded, after examining field data, that a fundamentally-sound complex terrain model should include 1) buoyancy entrainment to provide initial spreading of the plume; 2) modification of the plume path to account for lift created by a terrain obstacle; and 3) larger increased diffusion coefficients to account for surface roughness and resultant turbulent energy.
1977	Mullen et al.	Presented the Aerovironment Multi-Source Terrain Model (AVMSTM) and reported that it was a useful tool for assessing the effect of changing source configurations and in identifying conditions which produce the highest impacts.

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TABLE 9 (continued)

Date	Author(s)	Contribution
1977	Sklarew et al.	Developed a model to calculate the reactive point source emissions impact in complex terrain.
1977	Lange & Sherman	Claimed that the three-dimensional, time-dependent, particle-in-cell (PIC) model calculations exhibited several advantages over steady state Gaussian models for assessment calculations.
1977	Lavery & Schulman	Described a Gaussian plume, point source diffusion model used to predict hourly, 3-hourly, and 24-hourly averages of SO_2 concentrations in the vicinity of four electric generating plants in New York State.
1977	Wilson et al.	Explained how a model should be validated in order to be accepted as practical.
1977	Burt	Presented the computer program for the EPA Valley model.
1977	Cramer et al.	Designed a model for a particular source and obtained accurate estimates of short-term ground-level concentrations.
1977	Fabrick et al.	Presented a detailed comparison of a number of models with major emphasis on the Gaussian type models and the Integrated Model for Plumes and Atmospherics in Complex Terrain (IMPACT), a finite difference model.
1977	Fabrick	Presented the computer program for the IMPACT model.
1978	Klemp & Lilly	Developed a numerical model for simulating the flow over a two-dimensional object.
1978	Miller	Recommended how values for lateral and vertical dispersion for flat, smooth terrain could be modified for use in complex terrain.
1979	Howard & Fox	Used a box model to show pollution distrition resulting from residential wood burning.

(continued)

TABLE 9 (continued)

Date	Author(s)	Contribution
1979	Isaacs et al.	Discussed the application of potential flow theory to a Gaussian source diffusion model in complex terrain.
1979	Sklarew & Mirabella	Described the successful application of the IMPACT model on numerous occasions by a variety of investigators.
1979	Smith & Ruch, Jr.	Reported that the Valley model indicated estimates of air pollution much higher than those observed in the Penobscot Valley of Maine.
1979	Meroney	Performed a statistical correlation of laboratory simulation model results and field data.
1979	Ellis & Liu	Summarized the results of a comparison of the data from numerous field investigations and the estimates from 54 alternative models.
1979	Sklarew & Tran	Claimed Gaussian models were not of much use in complex terrain and recommended the use of the IMPACT model.

TABLE 10. NUMERICAL, STATISTICAL, AND COMPUTER STUDIES

Date	Author(s)	Contribution
1901	Pickels	Presented the first mathematical description of the flow over a mountain.
1947a	Sutton	Discussed in detail the development of approximate formulae for point and line sources derived by the statistical analysis of large amounts of field data.
1955	Scorer	Presented a very detailed mathematical description of the variation with height of the amplitude of lee waves.
1963	Tanner	Presented the results of a statistical study of the temperature variations along the slopes of a moist and a dry mountain range.
1964	Orville	Discussed a numerical study of upslope winds.
1965	Shakina	Presented the results of a numerical study of the circulation above a nonuniformly-heated isolated mountain whose temperature was subject to irregular fluctuations.
1965	Hirota	Developed a numerical model which produced results in agreement with Long's (1955) water channel experiments.
1965	Konyakhina et al.	Numerically analyzed the non-linearity of slope winds.
1965	Blumen	Computed the vertical flux of horizontal momentum resulting from an isolated circular mountain.
1966	Thyer	Produced a numerical model that featured valley and slope winds, anti-winds, and vertical currents using extensive field data for development and verification.
1966	Holton	Derived equations for simulating the dynamics of wind oscillations above sloping terrain.

(continued)

TABLE 10 (continued)

Date	Author(s)	Contribution
1966	Khalkechev	Discovered that the Coriolis force had negligible effects on winds in a narrow valley, but had to be considered in a wide valley.
1967	Foldvik & Wurtele	Presented a pioneering work on the numerical solution of non-linear waves.
1968	Hino	Described a computer experiment on smoke diffusion over complex terrain.
1969	Burov	Described a technique for studying diffusion around a 100-m hill by means of stereo-photos and a computer.
1974	Manabe & Terpstra	Used numerical experiments to identify the effects of mountains on the general circulation.
1974	Leslie & Smith	Explored numerically the effectiveness of katabatic winds in dispersing pollutants and compared the results to field observations.
1975	Lin et al.	Presented numerical simulations of plume dispersion in complex terrain and compared the results to simulations of flow in towing tank experiments.
1975	Mahrer & Pielke	Presented the results of the application of a two-dimensional, numerical model of airflow over a mountain.
1976	Riley et al.	Developed a computer program to calculate the three-dimensional stratified flow around complex terrain for the case of very strong stratification.
1977	Haussling	Used a numerical technique and a model to demonstrate the transition of a viscous flow over an infinitely-long barrier from homogeneous to stably stratified conditions.
1977	Clark & Peltier	Described a numerical simulation of flow over an isolated obstacle.

(continued)

TABLE 10 (continued)

Date	Author(s)	Contribution
1977	Fabrick et al.	Compared Gaussian and grid-type models and concluded, "After careful review of the Gaussian evaluation tests, one reaches the conclusion that almost any desired result can be obtained given the range of options for the dispersion parameters, plume trajectory in complex terrain, etc., and the range of uncertainty in the observed wind speed, wind direction, and atmospheric stability."
1977	Furukawa	Used numerical experiments to determine the effect of mountains on airflow.
1978	Klemp & Lilly	Developed a numerical model for simulating the flow over a two-dimensional object.
1978	Wooldridge & Orgill	Revealed from numerical research a steady increase of diffusivity coefficients and momentum fluxes with height up to the level of the ridges.
1978	Ookouchi et al.	Conducted a numerical study of the effect of a coastal mountain on the land and sea breeze.
1979	Hunt & Snyder	Solved the advective diffusive equation around a three-dimensional hill using an eddy-diffusivity formulation.
1979	Smith	Reported that as progressively wider mountains were considered in a computer study, the wave drag of the flow over a mountain decreased and the flow became more nearly geostrophic.
1979b	Mason & Sykes	Used the three-dimensional numerical integration of the Navier-Stokes equations to approximate the flow over obstacles (see Mason and Sykes, 1979a).

TABLE 11. WIND TUNNEL, WATER CHANNEL, AND OTHER LABORATORY STUDIES

Date	Author(s)	Contribution
1953	Long	Described a three-layer, water channel simulation of the lee wave phenomenon observed at Bishop, CA.
1955	Long	Presented a trilogy on the flow of stratified fluids over and around an isolated object.
1970	Long	Used two fluids of different density to show the upstream effect of an obstacle.
1974	Lin et al.	Reported on towing tank observations of flow over and around an isolated mountain.
1977	Kitabayashi	Conducted a wind tunnel and field study of the wind flow upstream of a ridge.
1979	Graham et al.	Used field data and wind tunnel tests to demonstrate that high terrain upwind of a power plant stack restricted plume rise while it increased vertical spreading.
1979	Arya & Shipman	Described a detailed study of the separation bubble formed on the lee side of a ridge.
1979	Thompson	Successfully duplicated field results with a wind tunnel experiment.

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TABLE 12. ISOLATED MOUNTAIN STUDIES

Date	Author(s)	Contribution
1927	Koschmieder	Used balloons, kites, and gliders to study air flow around an isolated hill.
1955	Long	Presented a trilogy on flows of stratified fluids over and around isolated objects in the fluids.
1956	Scorer	Used the perturbation theory to compute the vertical displacement of a uniform airstream passing over a solitary hill.
1956	Scorer & Wilkinson	Discussed the lee pattern produced by an isolated hill.
1957	Wurtele	Presented a three-dimensional model of the eddy produced downwind of an isolated mountain.
1962	Frenkiel	Discussed wind profiles over an isolated hill and a ridge line perpendicular to the prevailing flow.
1965	Shankina	Presented the results of a numerical study of circulation above an irregularly heated isolated mountain.
1965	Hirota	Developed a numerical model which produced results in agreement with Long's (1955) water channel experiments.
1965	Blumen	Computed the vertical flux of horizontal momentum resulting from an isolated circular mountain.
1969	Burov et al.	Described a technique for studying diffusion around a 100-m hill by means of stereophotos.
1970	Long	Used two fluids of different density to show the upstream effect of an obstacle.

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TABLE 12 (continued)

Date	Author(s)	Contribution
1973	Kozhevnikov	Presented one linear and two non-linear models to describe flow around a mountain.
1974	Lin et al.	Reported on towing tank observations of the flow over a small hill.
1976	Merkine & Kalnay-Rivas	Presented the results of a study (based on theory) of flow over an isolated topographic feature.
1976	Blumen & McGregor	Presented a theoretical study of lee waves formed by an isolated hill.
1977	Clark & Peltier	Described a numerical simulation of flow over an isolated obstacle.
1978	Klemp & Lilly	Developed a numerical model for simulating the flow over a two-dimensional object.
1979	Hunt & Snyder	Solved the advective diffusive equation around a three-dimensional hill using an eddy diffusivity formulation.
1979a	Mason & Sykes	Compared the theoretical results on airflow over a ridge with observations of airflow over a 130-m hill (see Mason and Sykes, 1979b).
1980	Bradley	Measured the turbulent wind structure for neutral conditions using a 100-m tower at the crest of a 170-m hill.

TABLE 13. SUMMARY REPORTS

Date	Author(s)	Contribution
1929	Baldit	Presented a detailed summary of knowledge on the airflow approaching, passing over, and continuing downwind of a mountain range.
1931	Morgan	Presented a comprehensive review of the German literature on the airflow over mountains.
1938	Ekhart	Presented a comprehensive review of many theories on the flow over complex terrain.
1945	Army Service Services	Summarized the literature on mountain and valley winds.
1949	Defant	Summarized the theories and field data of many investigators of airflow in complex terrain.
1954	Corby	Reviewed most of the major works dealing with flows over and downwind of mountain ridges.
1960	Queney et al.	Summarized the literature on lee-wave phenomena (see Nicholls, 1973).
1965	Geiger	Presented tables showing the variation of insolation with time of year, latitude, orientation of the valley, and inclination of the slope.
1966	Smyth	Reviewed the knowledge of diffusion in complex terrain.
1967	Schroeder et al.	Reviewed the literature on airflow over coastal mountains.

(continued)

TABLE 13 (continued)

Date	Author(s)	Contribution
1968	The Energy Policy Staff	Reviewed the site-selection requirements for locating steam power plants, but did not mention that complex terrain locations required special consideration.
1969	Goltsberg	Summarized much of the Russian literature on the variation of wind regimes in hilly terrain.
1973	Walden Research	Presented the results of an application of the EPA Valley Model in 51 Air Quality Control Regions (see Burt, 1977).
1973	Nicholls	Updated the review of the literature on lee-wave phenomena (see Queney et al., 1960).
1976	Egan & Bass	Reviewed air quality modeling in complex terrain.
1977	Koch et al.	Used the results from 16 independent field investigations to evaluate complex terrain models.
1977	Fabrick et al.	Compared Gaussian and grid-type models and concluded, "After careful review of the Gaussian evaluation tests, one reaches the conclusion that almost any desired result can be obtained given the range of options for the dispersion parameters, plume trajectory in complex terrain, etc., and the range of uncertainty in the observed wind speed, wind direction, and atmospheric stability."
1978	Barry	Reviewed the contributions of Horace Benedict de Saussure who late in the 18th century determined that the air over the valley was cooler in the daytime, than that at the same altitude over the mountain slopes.
1979	Ellis & Lin	Summarized the results of a comparison of the data from numerous field investigations and the estimates from 54 alternative models.

SECTION 3

CHRONOLOGICAL LISTING OF REFERENCES

Each of the references in this section contains one or more of the following abbreviations:

AMS American Meteorological Society
AMS - Second Atmos. Diffusion Conf. Preprints of Second Symposium on Atmospheric Diffusion and Pollution, Santa Barbara, CA, Sept. 9-13, 1974.
AMS - Third Atmos. Diffusion Conf. Preprints of Third Symposium on Atmospheric Turbulence, Duffusion and Air Quality, Raleigh, NC, Oct. 19-22, 1976.
AMS - Fourth Atmos. Diffusion Conf. Preprints of Fourth Symposium on Turbulence, Diffusion and Air Pollution, Reno, NV Jan. 15-18, 1979.
AMS-APCA - Joint Conf. Preprints Joint Conference on Applications of Air Pollution Meteorology, Salt Lake City, UT, Nov. 29-Dec. 2, 1977.
Ann. Chim. Phy. Annales de Chimie et de Physique
Ann. d. Phy. Annales de Physique
APCA Air Pollution Control Association
Arc. M. Geophy. Biokli. Archiv fur Meteorologie, Geophysik und Bioklimatologie
Atmos. En. Atmospheric Environment
BAMS Bulletin of the American Meteorological Society
Beit. Geophy. Beitrage zur Geophysik
Beit. Phy. Atmos. Beitrage zur Physik der Atmosphaere
Beit. Phy. f. Atmos. Beitrage zur Physik der frien Atmosphaere
ENV Environment
EPA U.S. Environmental Protection Agency
ESSA Environmental Science Services Administration
ESRL Environmental Sciences Research Laboratory, U.S. Environmental Pro-Protection Agency
ES&T Environmental Science and Technology
Geophy. JRAS Geophysical Journal of the Royal Astronomical Society
Ger Beit. Geophy. Gerlands Beitrage zur Geophysik
Hort. Soc. Trans. Horticulture Society Transactions
Int. J. Air & Wat. Poll. International Journal of Air and Water Pollution
Iz., Atmos. & Oc. Phy. Izvestia, Atmospheric and Oceanic Physics
JAPCA Journal of the Air Pollution Control Association
JAM Journal of Applied Meteorology
JAS Journal of Atmospheric Sciences
J. C. Phy. Journal of Computational Physics
J. Fl. Mech. Journal of Fluid Mechanics
J. For. Journal of Forestry

JGR	Journal of Geophysical Research
JIF	Journal of the Institute of Fuel
J. of M.	Journal of Meteorology
JMSJ	Journal of the Meteorological Society of Japan
Mech. Eng.	Mechanical Engineering
M. i. G.	Meteorologiia i Gidrologiia
M.Z.	Meteorologische Zeitschrift
MRW	Monthly Weather Review
NATO	North Atlantic Treaty Organization
Naturw	Naturwissenschaften
NAWC	North American Weather Consultants
NOAA	National Oceanic and Atmospheric Administration
Ohio Biol. Surv. Bull.	Ohio Biological Survey Bulletin
QJRMS	Quarterly Journal of the Royal Meteorological Society
Trans. AGU	Transactions of the American Geophysical Union
WMO	World Meteorological Organization
ZAMM	Zeitschrift fur Angewandte Mathematik und Mechanik
Z. M.	Zeitschrift fur Meteorologie
ZOGM	Zeitschrift Oesterriechiche Geschichte Meteorologische
ZOM	Zeitschrift Oesterriechiche Meteorologische

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1826 Daniell, J. R. On Climate Considered with Regard to Horticulture. Soc. Trans. 6:1-29. 1826.
First description of cold air moving down the slopes of hills and filling valley locations at night. Author noted that valley locations in fair weather at night were generally colder than the surrounding slopes and ridges.

1840 Fournet, M. J. Des Brises de Jour et de Nuit Autour des Montages. Chim. Phys. 74:337-401. 1840.
First published report describing typical daytime upvalley and nocturnal downvalley flows during fair weather in mountainous terrain.

1866 Hann, J. V. Zur Frage Uber den Urspring des Föhn. ZOGM 1:257-263. 1866.
First report on detailed observations of airflow in a mountain valley. He described the strong downslope wind (foehn) and explained the warming as the release of latent heat on the windward side and adiabatic warming on the leeward side of the mountain during descent.

1870 Berger. Theorie der Berg-Und Talwinde. ZOM 5:481-490. 1870.
First hypothesis on the causes of mountain and valley flows.

1879 Hann, J. V. Zur Theorie der Berg-Und Talwinde. ZOGM 14:444-448. 1879.
Early hypothesis on the cause of the mountain and valley flows. Author concluded that winds resulted from expansion and contraction of layers of air in various parts of the valley system.

1901 Pockels. Zur Theorie der Niedershlagsbildung an Gebrige. Ann. d. Phy. IV:459-480. 1901.
A very early mathematical treatment of the flow of air over a mountain. Assumed simple conditions of flow and a periodic surface profile.

1910 Defant, A. Zur Theorie der Hangwinde, Nebst Bemerkungen Zur Theorie der Berg-Und Talwinde. M. Z. 27:161-168. 1910.
Hypothesized that pressure gradients were primarily responsible for the fair weather mountain-valley flows.

1914 Hesselberg, T. and H. V. Siverdrup. Uber den Einfluss der Geirge Auf Die Luftbewegung Lands der Erdoberflache Geophysikalisches Institut (Leipzig Universitat), Veroffentlichungen, 2nd Ser. 1:101-116. 1914.
Reported there was a close relationship between isobars and streamlines even in mountains. The mountains influenced streamlines 1) by causing local divergence and convergence points (in such a way that during winter

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morning, divergence points are always over the mountains, and convergence points over the plains) and 2) by altering the course of streamlines. Their findings were illustrated by charts of streamlines and isobars across the Alps.

1920 Young, F. D. Effect of Topography on Temperature Distribution in Southern California. MWR 48:462-463. 1920.
Showed that a long uniform slope rising at a slight angle did not cause the same thermal variation and associated drainage as a steep slope. The author noted that the warmest location on a clear night was often displaced a short distance down from the summit.

1923 Cox H. J. Thermal Belts and Fruit Growing in North Carolina. MWR Supplement 19. U.S. Weather Bureau, Washington, DC. 107p. 1923.
Noted that 1) a plateau-like area near a summit was necessary for the development of a downslope wind, 2) coves, shelves, and benches temporarily stopped downslope flows until enough cold, dense air accumulated, and 3) the size of the valley, angle of slope, and the proximity of slopes affected the downslope winds. Further noted that maximum temperatures were much higher in the winter on a southerly than on a northerly slope and in all seasons of the year higher on a westerly than on an easterly slope.

1923 Werner, R. Zur Theorie der Berg-Und Talwind. M. Z. 40:193-?04. 1923.
Explained the mountain-valley flow by applying the circulation theorem of V. Bjerknes to a triangular path along a plane leading up a slope, then along an isobaric surface, and vertically down to the plain.

1924 Pollak, L. W. Berg-Und Talwind in Bergen von Trient. M.Z. 41:18-21. 1924.
Observed that the mountain wind dissipated from above in a rather deep valley near Trento, Italy. Mountain wind heights decreased as much as 700 m during a period of several hours after sunrise (see Ayer, 1961 and Whiteman and McKee, 1977).

1927 Koschmieder, H. Die Luftstromungen am Berghindernisse in der Frien Atmosphare. Beit. Geoph. 15:285-303. 1927.
Described the field of flow about a hill and about a mountain. Used observations from balloons, kites, and gliders.

1929 Baldit. A. Meteorologie du Relief Terrestre. Vents et Nuages. Paris, Gauthier-Villars. 328 pp. 1929
Wrote one of the first textbooks describing wind flows over mountains and chains of mountains. Showed the eddy created

on the upwind side of a mountain, the complex flow which evolves when wind flows across an intermountain valley, plane and elevation views of winds flowing through mountain passes and the eddy created on the downwind side of the mountains. In a composite picture he showed that the flow over a mountain had five parts moving in a downwind direction: 1) discontinuity surface; 2) ascending current zone; 3) descending current zone; 4) abruptly changing atmospheric turbulence; and 5) undulations.

1931 Ekhart, E. Zur Aerologie der Berg-Und Talwindes. Beit. Phy. f. Atmos. 18:1-26. 1931.

Used pibal data from Alpine stations to show the diurnal vertical variations of mountain and valley winds. Upvalley winds generally prevailed from an hour or two after sunrise to an hour or two after sunset. The wind speed of the upvalley flow generally increased from its onset until the middle of the afternoon and then slowly decreased. Maximum speeds at the surface during the afternoon ranged from 3 to 8 mps. The maximum speed in the vertical was several hundred meters above the surface and usually averaged about 10 mps. The nocturnal flows were downvalley with speeds of 2 to 3 mps at the surface and 3 to 4 mps aloft. Within the valley there was frequently a reverse flow of anti-winds above the winds in the valley bottom. The upvalley flow usually attained its maximum depth within an hour or two of its onset.

1931 Athmanathan, S. The Katabatic Winds at Poona. Sci. Notes, India Meteorol. Dep. 4:101-115. 1931.

Showed that downvalley winds at Poona, India, which is at the confluence of two river valleys, alternated from the southwest and north-northwest. Each wind occurred with various speeds up to 10 mph on clear, calm nights in the cold season. When cloudy skies prevailed there were no downslope winds.

1931 Morgan, W. F. A memorandum giving a summary of present knowledge on the relationship between ground contours, atmospheric turbulence, wind speed and direction. Aeronautical Research Commission Technical Report for 1932. Memo #1456. 39 pp. 1931.

Reviewed the literature, primarily contributed by German investigators, and summarized knowledge as of 1931. Discussed 1) the height and horizontal distance of the influence of obstacles; 2) the depth (down from summit) of the influence of a mountain; 3) the flow over an isolated mountain; 4) the theoretical treatment of the flow of air over a mountain; 5) the comparison of the theory with the field results; 6) the eddies in the neighborhood of obstacles; 7) the effects of coasts; and 8) the vertical velocities.

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1932 Ekman, V. A. Uber die Beeinflussung der Windbahen Durch Gebirge. Beit. Phy. f. Atmos. 19:272-275. 1932.
Discussed the dynamics of wind flow in mountainous areas based on the theory of Hesselberg and Sverdrup (1914) and observations in Alpine areas.

1932 Lange, K. L. Uber Vertikalbewegungen der Luft in der Atmosphare. Rhon-Rossitten Gesellschaft e.V., Forchungsinstitut, Veroffentlichungen 5:25-43.
Released no-lift balloons from aircraft at various heights above hilly country near Wasserkuppe (950 m) and tracked with two theodolites. Tracks are shown in plane and elevation views. Results are summarized under temperature gradient and wind speed. With winds of 0.5 mps and large temperature gradients, flow was independent of contours. With stable stratification and light winds, flow was laminar; with stronger winds (8+mps) only the main features were followed. With gradients and differential heating of the slopes there was a combination of contour and thermal winds.

1933 Heywood, G.S.P., Jr. Katabatic Winds in a Valley. QJRMS 59:47-58. 1933
Described characteristics of downslope winds. Katabatic flows usually had speeds of 1 mps or less, began in the evening, terminated a few hours later, were very shallow at first, and then expanded to a depth of 40 feet with the strongest flow 15 to 20 feet above the surface. Katabatic winds accompanied only weak to moderate inversions on the upper slopes (the source of the cold air that drains downslope). When the inversion between 4 and 100 feet exceeded 5°F, there seldom were downslope flows. Though the use of smoke in the early evening showed that while there were downslope winds immediately above the surface, there was upslope flow above the downslope flow. While there was a katabatic wind flowing in the valley, winds in the open (away from the valley) never exceeded 5 mps.

1934 Schell, I. I. Differences Between Temperatures, Humidities, and Winds on the White Mountains and in the Free Air. Trans. AGU Reports and Papers, Meteorology--1934:118-133. 1934.
Documented the temperatures in the free air and simultaneous observations along the slopes on clear days. Flying an aircraft in the vicinity of the Presidential Range and the White Mountains in New Hampshire, the author recorded temperatures at numerous heights over the valley while temperatures were continuously recorded at 10 stations along the slopes. The temperatures along the slopes (about 1 m above the surface) were higher than those in the free air and showed lapse rates less than adiabatic. Over the valley, the lowest 360 m showed a superadiabatic lapse rate

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while above that layer the lapse rate was less than adiabatic. On clear nights, the mountain tops and slopes cooled more rapidly than the air in the free atmosphere at the same level. Soon after the air on the slopes became cooler than the air over the valley, cooling on the slopes was retarded due to the sinking of the cold air and its replacement by the adjacent warmer air at the same level.

1935 Moll. E. Aerologische Utersuchung Periodischer Gebirgswinde in V-Formingen Alpentulern. Beit. Phy. f. Atmos. 22:177-199. 1935.

Presented profile views of 1) the wind flow in a V-shaped, 25-km long, lateral valley and 2) the upslope flow on a south-facing slope with a 45¼ inclination. In the lateral valley on a clear day the upvalley flow practically filled two-thirds of the valley depth and there was an antiwind or downvalley flow. On the 700-m long slope, the upslope flow was 10 m deep 150 m up the slope, about 50 m deep 200 m up the slope and 100 m deep at the top of the slope. The author cautioned that the layer thickness was dependent on the valley size and slope inclination.

1937(a) Jelinek, A. Beitrage Zur Mechanik der Periodischen Hangwinde. Beit. Phy. f. Atmos. 24:60-84. 1937(a).

Presented a detailed description of slope winds. His points were:

1) Thermal slope winds with definite diurnal periods developed on all of the slopes investigated. As expected, the best developed thermal slope winds occurred along south-facing slopes at the time when solar isolation was the strongest. North-facing slopes, on the other hand, showed the most unfavorable conditions for slope flow, being unsteady and much less influenced by other disturbances. East- and west-facing slopes ranged approximately in the middle of these effects.

2) As measured by the strength of the surface winds during the day, the upslope winds were arranged in the following order according to the direction the slope faced: south, west, east, and north. Usually, the surface wind speed along the south-facing slope was almost three times that along the north-facing slope. At night (downslope wind) the north facing slopes shifted to second place. The wind speed maxima behave in similar fashion along the different slopes.

3) On all slopes, the slope wind followed the solar angle but with a small phase delay. The wind reversal occurred about from one-fourth to three-fourths of an hour after

sunrise and sunset, respectively, occurring earlier on the south- and west-facing slopes than on the north and east. The south-facing slope had the longest duration of upslope winds.

4) At the time of the wind reversal, the valley wind frequently penetrated up to the slope.

5) In general, the daytime upslope wind presented the best developed component of the slope wind system (analogous to the valley wind).

6) Both the strength of the upslope winds and also the thickness of the layer grew with increasing solar angle.

7) The thickness of the layer of upslope winds was measured to a maximum of 260 meters on the south-facing slope.

8) The vertical component of the slope wind system reached a magnitude of about 4 mps and was greatest in the middle of the layer during all daytime hours. The region of maximum vertical wind speeds shifted in parallel with the upper limit of the slope wind in the course of the day.

9) Frequently a portion of the upslope wind changed because of the presence of cumulus clouds. Often a considerable vertical displacement of air was measured under a cloud formation, measuring 13 mps in one case.

10) Surface irregularities such as draws and prominences and the like, often influenced the slope flow markedly. In general, it can be said, in agreement with Riedel, that at exposed locations, counter flows, such as valley winds and gradient winds, could easily penetrate. Depressions along the slope presented excellent channels for the slope winds.

1937(b) Jelinek, A. Uber den Thermischen Aufbau der Periodischen Hangwinde. Beit. Phy. f. Atmos. 24:85-97. 1937(b).
Reported that the slope winds in Alpine areas were least pronounced because the vertical temperature gradients were smallest. He further noted that downslope winds developed primarily in the layer of air from the ground up to 20 feet; at a height of 40 feet, the speed dropped to one-third the speed observed near the surface.

1938 Wagner, A. Theorie und Beobacktung der Periodischen Gebirgswindes. Ger. Beit. Beophy. 52:408-449. 1938.
Discussed the theory and observations of slope winds. Showed both upslope and downslope winds increasing in depth with distance. In the upper reaches on steep slopes in the Inn Valley, the depth of the upslope winds was as great as 300 m (normal to the slope).

1938 Conford, C. E. Katabatic Winds and the Prevention of Frost Damage. QJRMS 64:553-589. 1938.
Summarized a two-year investigation of katabatic flows on a 200-foot hill with a one-in-three slope. Reported that katabatic winds were usually only 15 feet deep and seldom had a speed exceeding 1 mps. On clear nights when the hilltop wind direction was opposite that of the katabatic wind, the upper slope had upslope winds. Frequently, the upslope wind was separated from the katabatic flow by a 12-foot wide area with calm conditions. Short hedges would temporarily stop a katabatic flow but eventually the flow would move up over the hedges. Katabatic flows moving downslope varied over a wide range.

1938 Ekhart, E. Die Tageszeitenwinde der Alpen. Naturw. 26:21-27. 1938.
Presented a comprehensive review of theory. He agreed with parts of Von Hann's theory, and held that the true mountain wind is a circulating current as Wegner, Wagner, Ekhart and others contended.

1940 Fons, W. L. Influence of Forest Cover on Wind Velocity. J. For. 38:481-486. 1940.
Presented wind speed profiles obtained in and over (to 142 feet above ground) a Ponderosa Pine Forest. The upper canopy was approximately 70 feet high. In the canopy area, speeds were generally 20 percent of the speeds at 100 feet and higher; the forest retarded and diverted the flow.

1941 Hayes G. L. Influence of Altitude and Aspect on Daily Variations in Factors of Forest-Fire Danger. U.S. Dept. Agri. Circ. No. 591. 38 p. 1941.
Compared temperature and wind data gathered each August from 1935 through 1938 from six pairs of stations at matched elevations on slopes with north and south aspects. Each site was in the west to 5800 feet in the east. At the lower elevations, temperatures were warmer on the southside of the ridge. At higher elevations at night, there were minimal differences in temperature, while in the remainder of the day, temperatures were slightly higher on the north aspect. Temperature inversions formed

earlier and dissipated later on the south-facing slope. The report contains several detailed summaries on the diurnal variation of temperatures and wind speeds.

1943 Lyra, G. Theorie der Station Aren Leewellenstromung in Freier Atmosphare. ZAMM 32:1-28. 1943.
Derived a lee wave equation and presented the mathemetical formulation. Many who described lee waves in later years (e.g., Merbt, 1959) based their analyses on the Lyra formution.

1944 Hewson, E. W. and G. C. Gill (In Report Submitted to the Trail Smelter Arbitral Tribunal by R. S. Dean and R. E. Swain). Meteorological Investigations in Columbia River Valley Near Trail. U.S. Government Printing Office, Washington, DC. pp. 23-228. 1944.
Documented to the satisfaction of the international tribunal that the air pollution problem in the 50-mile long Columbia River Valley from Trail, British Columbia into the U.S. was caused by fumigation that occurred early in the morning. Showed daytime upvalley and nocturnal downvalley winds were accompanied by opposing flows or anti-winds at upper levels. Indicated low-level winds frequently had a cross-valley component. Showed the effect of side valleys on the flow in the main valley, which was 0.5 to 3.0 miles wide and summarized the effect of turbulence. Suggested "meteorological control" for the source operation: emit during favorable meteorological conditions and do not emit during unfavorable conditions.

1945 U.S. Army Air Forces. The Structure of the Local Winds in the Los Angeles Basin, California. Tech Report 105-1. Asheville, NC. 11 pp. 1945.
Summarized the results of a large number of slow-ascent pilot balloon observations over Los Angeles. Discussed the interaction of land and sea breezes with mountain and valley winds.

1945 Army Service Forces. Local Winds. Dugway Proving Ground, Tooele, UT. Report No. 982. 45 pp. 1945.
Summarized the literature (much of which was in German) on mountain and valley winds and presented a three-dimensional view on how these winds varied diurnally.

1945 Johnstone, H. F., W. E. Winsche, R. L. LeTourneau, and W. L. Smith. Some Theoretical Aspects of the Behavior of DDT Aerosols Dispersed from Aircraft. Office of Scientific Research and Development, University of Illinois. 35 pp. 1945.
One of a series of reports from teams of experts from universities, industry, and government (U.S. and British) who studied the dispersal of aerosols. Wind tunnel and

field investigations were conducted. Although these investigations dealt with diffusion and turbulence theory, they made the results relevant to the practical problem of getting the aerosol to the ground in all kinds of terrain.

1945 Manley, G. The Helm Wind of Crossfell, 1937-1939. QJRMS 71:197-219. 1945.
Documented and described the flow of strong winds over a summit and the complicated flow in the valley on the downwind side.

1945 Hewson, E. W. The Meteorological Control of Atmospheric Pollution by Heavy Industry. QJRMS 71:266-282. 1945.
Described a comprehensive field investigation of a major air pollution problem in complex terrain. He documented that the problem involved longrange transport to at least 50 miles; and concluded that the worst problem occurred with fumigation in the morning. This work contained excellent documentation on the air movement and concentration of a pollutant in three dimensions.

1946 Hewson, E. W. Discussion of the Meteorological Control of Atmospheric Pollution by Heavy Industry. QJRMS 72:51-54. 1946.
Discussed the details of the field study in Canada. Reference was made to the meteorological considerations involved with radioactive air pollution at Hanford, WA and Clinton, TN. Discussed the idea of meteorological control of industry in Great Britain. Was unable to detect katabatic winds at a height of 10 m.

1947a Sutton, O. G. The Problem of Diffusion in the Lower Atmosphere. QJRMS 73:257-281. 1947a.
Discussed in detail the development of approximate formulae derived by the "statistical method" for point and line sources. Showed the relation between "statistical" and "mixing length" theories. Although reported by Sutton, author acknowledged that major contributions were made by E. Davies, A. C. Best, P. A. Sheppard, K. L. Calder, H. Garnett, F. Pasquill, and C.H.B. Priestly. For lack of other formulae, the Sutton formulae were used in computing diffusion in complex terrain during the late 1940's and 1950's.

1947 Quency, P. Theory of Perturbations in Stratified Currents with Applications to Airflow over Mountain Barriers. Univ. Chicago Misc. Rep. Met. Dept. No 23.
Discussed the perturbation theory which many investigators (Scorer, 1949 and Curby, 1954) applied to flow over ridges and ranges.

1947b Sutton, O. G. The Theoretical Distribution of Airborne Pollution from Factory Chimneys. QJRMS 73:426-436. 1947b.
Presented a method for computing downwind ground concentrations from a large point source. Compared calculated results to results obtained at a large point source in complex terrain. This method of calculating downwind concentrations was used for many years in operational programs at pollution sources in complex terrain.

1948 Neuberger, H. Condensation Nuclei. Mech Eng. 70:221-225. 1948.
Indicated that vegetation effectively removed both gaseous and particulate matter.

1949 Schrenk, H. H., H. Heimann, G. D. Clayton, W. M. Gafafer, and H. Wexler. Air Pollution in Donora, PA. Public Health Bulletin No. 306. Washington, DC. 173 pp. 1949.
Described in detail the wind flows typical of the air stagnation associated with the air pollution disaster. On the mornings with stagnation, there was generally a flow from the north near the surface averaging about 2.5 mph. Higher above the mid-valley floor the flow was from the south, averaging about 1.5 mph. In the shear area between the opposing flows there was an air exchange.

1949 Defant, F. Zur Theorie der Hangwinde, Negst Bemerkungen Zur Theorie der Berg-Und Talwinde. Arc. M. Geophy. Biokli.
Compared theories on valley flow with field observations and described slope winds in detail. Included an eight-part diagram showing the diurnal variation of valley and slope winds. (This diagram was based on the verbal description of Wagner, 1938). Through the use of double-theodolite pilot-balloon ascents, determined that the downslope wind layer was between 50 and 100 m deep with a maximum speed at about 30 m. The upslope wind layer was 100 or more meters deep with a maximum speed at about 30 m. The average speeds of the upslope winds were markedly greater than those of the downslope winds. (See also a similar article, Local Winds, in the Compendium of Meteorology, Defant, 1951.)

1949 Woelfe, J. N., R. T. Wareham, and H. T. Scofield. Microclimates and Macroclimate of Nedtoma, A Small Valley in Central Ohio. Ohio Biol. Surv. Bull. 41. Ohio State Univ., Columbus. 267 pp. 1949.
Discovered that drainage winds did not move cold air into crevices and grottoes in low-lying parts of the valley. These areas were shielded and did not radiate directly to the atmosphere.

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1949 Scorer, R. S. Theory of Waves in the Lee of Mountains. QJRMS 75:41-56. 1959.
Presented a theory valid for streamline, dry, isentropic, invisid flow in which the disturbance is only a small proportion of the wind velocity.

1949 Hales, W. B. Micrometeorology in the Tropics. BAMS 30:124-137. 1949.
Reported that lapse conditions prevailed above and inversions below a dense forest canopy during the daytime, while radiational cooling of the canopy produced the opposite effect at night.

1949 White, R. M. The Role of the Mountains in the Angular Balance of the Atmosphere. J. of M. 6:353-355. 1949.
Documented the pressure difference across a mountain range using snyoptic pressure patterns. Discovered that mountains normally acted to abstract angular momentum from the atmosphere in mid-latitudes and to supply such momentum to the atmosphere in low latitudes.

1950 Shanks, R. E. and F. H. Norris. Microclimate Variation in a Small Valley in Eastern Tennessee. Ecology 31:532-539. 1950.
Documented the time variation of temperature at several heights along a slope. Presented an example of a breeze (parcel of warm air) moving slowly downslope. Found the bottom of the katabatic flow to be about one foot above the surface.

1951 Cross, C. M. Slope and Valley Winds in the Columbia River Valley. BAMS 31:79-84. 1950.
Noted that in the Columbia River Valley, where it was 0.5 to 3 miles wide and 2000 to 4000 feet, katabatic winds were seldom detected at 40 feet above the slopes.

1952 Smalley, C. L. Unusual Vertical Air Currents in the Vicinity of Warm Springs, California, October 29, 1950. BAMS 33:299-302. 1952.
Described unusual vertical currents observed over complex terrain south of San Francisco Bay.

1952 Braham, R. R., B. K. Seely, and W. D. Crozier. A Technique for Tagging and Tracing Air Parcels. Trans. AGU 33:825-833. 1952.
Described an experiment in which an aerosol plume was tracked out to a distance of 107 miles over mountainous terrain in New Mexico. Showed particle concentrations in the horizontal and vertical.

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1952 Colson, D. Discussed Results of DoubleTheodolite Observations at Bishop, Cal. in Connection with the "Bishop-Wave" Phenomenon. BAMS 33:107-116. 1952.
Presented several examples of the standing (Bishop or Sierra)-wave pattern. In some cases, the location of the up and downdrafts, as well as the horizontal wavelength, were determined.

1953 Gleeson, T. A. Effects of Various Factors on Winds. J. of M. 10:262-269. 1953.
Derived an expression for the horizontal components of the valley wind as functions of the slope of the floor, turbulent heat conduction, and turbulent friction. The theory applied only to the mid-valley.

1953 Holland, J. Z. A Meteorological Survey of the Oak Ridge Area: Final Report Covering the Period 1948-1952. ORO-99, Technical Information Service, AEC, Oak Ridge, Tennessee. 584 pp. 1953.
Presented a detailed summary of the meteorological parameters affecting dispersion in the mountainous area in and around Oak Ridge, TN.

1953 Long, R. R. A Laboratory Model Resembling the "Bishop-Wave" Phenomenon. BAMS 34:205-211. 1953.
Described the results of a water channel simulation of the flow of a three-layer system of immiscible fluids over an obstacle immersed in the lowest layer. Suggested that some features of the observed motion may be similar to the flow of air over the Sierra Range near Bishop, CA.

1953 Scorer, R. S. Theory of Airflow over Mountains: II-The Flow over a Ridge. QJRMS 79:70-83. 1953.
Defined three kinds of flow over unlevel ground according to their scale-aerodynamic, barostromatic, and geostrophic; showed the difficulties in obtaining the correct value of the non-dimensional numbers in model experiments were almost prohibitive; reported that the disappearance of the adiabatic layer at the ground at the end of the day maximized the orographic effects around sunset on sunny days; and related the diurnal variations in the wavelength of lee waves to the development and disappearance of this adiabatic layer at the ground.

1954 Corby, G. A. The Airflow over Mountains: A review of the State of Current Knowledge. QJRMS 80:491-251. 1954.
Reviewed most of the major works dealing with flows over and downwind of mountain ridges.

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1954 Radock, U. A Procedure for Studying Mountain Effects at Low Levels. BAMS 35:412-416. 1954.
Obtained a representative picture of vertical currents above mountainous terrain by letting these currents act on an aircraft set to fly horizontally in still air. Two sets of results were shown. One showed low-level waves which were caused presumably by a temperature inversion; the other was a case of strong turbulence side-by-side with a smooth wave in which downdrafts reached 1600 ft/min in an 18-knot wind.

1954 Colson, D. Meteorological Problems in Forecasting Mountain Waves. BAMS 35:363-371. 1954.
Described work being done to improve forecasting of standing waves in complex terrain. Indicated the meteorological phenomena typically associated with standing wave.

1955 Stapley, C. E. Summary of Mean Streamline Patterns for Dugway Proving Ground, 1952-1954. Meteorology Division, Technical Services. Dugway Proving Ground, Toole, UT. 179 pp. 1955.
Presented streamline flow charts for a 30 by 30-mile part of the valley around Dugway for all odd-numbered hours for each month. Excellent display of the wind variations on a small scale.

1953 Long R. Some Aspects of the Flow of Stratified Fluids. Part I. Tellus 5:42-58; Part II. Tellus 6:97-115; Part III. Tellus 7:341-357.
Studied the effect of a solitary obstacle on gravity waves and presented experimental results (see Hirota, 1965).

1955a Scorer, R. S. Theory of Airflow over Mountains. Part III-Airstream Characteristics. QJRMS 80:417-428. 1955a.
Presented a very detailed mathematical explanation of the variation with height of the wave amplitude of lee waves.

1955b Scorer, R. S. Theory of Airflow over Mountains: Part IV-Separation of Flow from Surface. QJRMS 81:340-350. 1955b.
Reported that the separation of flow at ridges may be two-dimensional when the wake of an eddy was closed, or three-dimensional when the air was continuously replaced. Showed that eddies may be formed on both the windward and leeward side of a mountain range as the winds flowed perpendicular to the range and noted that the air near the summit on the lee side could be stagnant as a result of the lee wave.

1955 Forchgott, J. The Measurement of Airflow Deformation Behind Mountains. QJRMS 81:488-493. 1955.
Documented the thermal structure of lee waves with glider and radiosonde observations and reported that the temperature was less in the wave crest and greater in the wave trough than in between, where it was equal to that of the undisturbed stream.

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1955 Meikeljohn J. The Local Wind at Milfield, North Umberland. QJRMS 81:468-474. 1955.
Noted that the strong surface winds in the valley at Milfield frequently were only 100 feet in depth even though the valley depth was 1000 feet.

1956 Scorer, R. S. Airflow over an Isolated Hill. QJRMS 82:75-81. 1956.
Used the perturbation theory to compute the vertical displacement of a uniform airstream passing over a solitary hill for a circular hill; for a hill of an oval section lying across the wind; obliquely to it; and along it.

1956 Corby, G. A. and C. E. Wallington. Airflow over Mountains: The Lee-Wave Amplitude QJRMS 82:266-274. 1956.
Discussed the theory of lee-waves over the British Isles.

1956 Scorer, R. S. and M. Wilkinson. Waves in the Lee of an Isolated Hill. QJRMS 82:419-427. 1956.
Discussed the lee patern produced by an isolated hill.

1957 Yoshino. Y. The Structure of Surface Winds Crossing a Small Valley. JMSJ 35:184-185. 1957.
Noted that with light winds crossing a ridge, a lee eddy was formed at certain intervals. The one immediately downwind of the ridge caused a backward or upslope current on a steep slopes near the summit. As a result, the upper part of the slope experienced the minimum wind speed. This was not the case where the slope was gentle. On the exposed slope, the winds were weakest at the valley bottom and strongest at the summit; there was no reversal flow on the windward side.

1957 Dickson, C. R. A Synoptic Climatology of Diurnal Inversions in the Jordon Valley. Dept. of Meteorol., Univ. of Utah, Salt Lake City, 82 pp. 1957. Noted that the Jordan Va
Noted that the Jordan Valley, which is 16 miles wide and 20 miles long and has an average depth of 1500 feet, had inversions which averaged 770 feet in depth. Noted that katabatic winds were observed on practically every night that the regional pressure gradient was weak and the skies were clear.

1957 Wurtele, M. G. The Three-Dimensional Lee Wave. Beit. Phy. Atmos. 29:242-252. 1957.
Presented a model assuming an isothermal atmosphere with no shear in the basic current. With small perturbations, it was possible to compute vertical velocities resulting from an isolated mountain at distances from the mountain greater than stationary wave length (about 5 kilometers).

1958 Corby, G. A. and J. S. Sawyer. The Airflow over a Ridge. The Effects of the Upper Boundary and High-Level Conditions. WJRMS 84:25-37. 1958.
Discussed the effects on the flow downwind of a ridge when the high-level condition was treated as a rigid lid.

1958 Thompson, A. H. and C. R. Dickson. Ground Layer Temperature Inversions in an Interior Valley and Canyon. Dept. of Meteorol., Univ. of Utah, Salt Lake City. 136 pp. 1958.
Used data from five towers, each 16 m or taller, on various slopes to discover that temperature inversions generally extended to the top of each tower. Slopes were seldom without a katabatic flow.

1959 Buettner, K.J.L. and H. Thyer. On Valley and Mountain Winds. Dept. of Meteorology and Climatology, Univ. of Washington, Seattle. Final Report of Contract 19(604)-2289. 1959.
Noted shortcomings in the widely publicized Defant-Wagner depiction. These errors were 1) the upslope winds were separate from the valley winds and the downslope winds were separate from mountain winds; 2) the double cell required downward motion in the middle of the valley in the daytime and the reverse at night (neither was observed); and 3) insulation on valley sides in steeper valleys was not symmetrical (so cross-valley winds readily developed).

1) Discovered that daytime valley and nocturnal mountain winds occurred regularly and generally filled the valley to near the ridge level; 2) observed compensating currents or anti-valley and anti-mountain winds were about 300 m above the ridge level; 3) discovered that currents in the valley and their respective anti-winds were separated by a highly irregular mixing layer 200-300 m in thickness; and 4) concluded that length, height, steepness of sides of the valley, as well as well-defined distal and proximal ends, determined how well-developed a valley wind system could become.

1959 Kassander, A. R., Jr. A Study of the Trajectories and Diffusion Patterns of Ground-Generated Airborne Particulates Under Orographic Wind-Flow Conditions. J. of M. 16:617-625. 1959.
Performed a series of experiments in the Rincon Valley near Tucson, AR to determine the wind structure over an orographic barrier. Zinc sulfide particles dispersed in an oil fog were used as a tracer and airborne impactors were used as collectors. Particles were found at elevations of 14,000 feet at distances to at least 20 miles. However, plumes were found to be considerably broader than had been anticipated based on assumptions used in cloud-seeding operations.

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1959 Merbt. H. Solution of the Two-Dimensional Lee-Wave Equation for Arbitrary Mountain Profiles, and Some Remarks on the Horizontal Wind Component in Mountain Flow. Beit. Phy. Atmos. 31:152-161. 1959.
Transformed the two-dimensional lee-wave equation to elliptical coordinates and solved it in terms of Mathieu functions for arbitrary forms of the mountain profile. In the case of a plateau, the solution reduced to Lyra's (1943) solution.

1960 Queney, P., G. A. Corby, N. Gerbier, H. Koschmieder, and J. Zierep. The Airflow over Mountains. WMO Tech. Note 34. Geneva, Switzerland. 135 pp. 1960.
Presented a thorough review of the literature on lee-wave phenomena.

1960 Thyer, N. and K.J.K. Buettner. On Valley and Mountain Winds II, Univ. of Washington, Seattle. Dept. of Meteorol. and Climatol. AFCRL-250. 20 pp. 1960.
Presented a detailed documentation of wind profiles for three or more locations across individual valleys. No-lift and very slow ascension rate balloons were used to determine that vertical currents were strong and localized vertical currents were concentrated near the summits of the sides forming the valley. The main area of exchange between the slope flows and the valley winds was the ridge level area.

1960 Doos, B. R. A Mountain Wave Theory Including the Effect of the Vertical Variation of Wind and Stability. Interntl. Meteorol. Inst., Univ. of Stockholm, Sweden, Tech. Note No. 2. pp. 305-319. 1970.
Reported on the study of motion over an infinitely long mountain ridge and related results to theory.

1960 Sinha, M. C. Upper-Air Standing Waves over Kabul Valley. Beit. Phy. Atmos. 32:215-236. 1960.
Discovered from a detailed two-week study in November 1958, that sets of well-formed air standing waves superposed upon each other were actually over the valley on most occasions. These waves generally existed during fair weather, but with the approach of disturbances broke down into a turbulent flow. The waves reappeared when the disturbances moved away.

1960 Von Eschen, G. F. Nighttime Temperature Rises in Mountain Canyons. MWS 88:70-71. 1960.
Studied a nocturnal temperature anomaly in Cedro Canyon in the Manzano Mountains, 25 km east of Albuquerque, NM. Temperatures were known to rise rather abruptly around midnight, so an investigation was conducted through 1959.

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It was found that on 42 percent of the nights, there were rises and falls varying from several degrees to as much as 12¼C. The rises were attributed to drainage winds which for varying periods of time dissipated the nocturnal inversions. The author speculated that the phenomenon was not unique and probably occurred in many other canyons in the West.

1961 Ayer, H. S. On the Dissipation of Drainage Wind Systems in Valleys in Morning Hours. J. of M. 18:560-563. 1961.
Observed that well-developed downvalley winds frequently dissipated from above as instability developed at the ridgetop level. Concluded that the inversion, which is shallower over the ridgetop area, burns off more readily than that over lower parts of the valley. (See Pollak, 1924; Whiteman and McKee, 1977.)

1961 Sterten, A. K. Local and Synoptic Meteorological Investigations of the Mountain and Valley Wind System. Part I: Local Meteorological Investigations of the Mountain and Valley Wind System in Southeastern Norway. Intern. Rep. K-242. Forsvarets Forskningsinstitutt. Norwegian Defense Res. Establ., Kjeller-Lillestrom, Norway. 139 pp. 1961.
Reported that as long as there was some clear sky between sunset and sunrise, the mountain wind appeared; the clearer the sky, the stronger and more stable was the mountain wind. Observed, through the use of smoke, that when mountain and valley winds converged in a valley, the head of the valley wind was diverted vertically and joined the remainder of the mountain wind which dominated the upper area to a height above the crest. Discovered that when the sky became overcast during a night with a mountain wind blowing, the wind became weaker or disappeared. Overall, the results demonstrated close relationship between the mountain and valley wind system and the interdiurnal variation in atmospheric pressure.

1961 Cramer, O. P. and R. E. Lynott. Cross-Section Analysis in the Study of Windflow over Mountainous Terrain. BAMS 42:693-702. 1961.
Used cross-section analyses of a 50-mile length over mountainous terrain to show changes in stability and stratification in the lowest 1000 m. Evidence indicated that vertical patterns of potential temperature should be considered in the detailed analysis of wind structure in mountain areas.

1961 Koch, H. G. Die Warme Hangzone. Z. M. 15:151-171. 1961.
Discovered a nocturnal threefold stratification across a valley and concluded that this stratification was not in accord with the temperature stratification of the slope. He further indicated that the accumulation of cold air in the valley bottom did not come from within the slope atmosphere or from lateral valley wind entrainment.

1961 Schroeder, M. J. Down-Canyon Afternoon Winds. BAMS 42:527-542. 1961.
Discovered that under certain conditions the typical daytime upslope wind would disappear and that transport opposite to that expected would occur.

1962 Thyer, N. and K.J.K. Buettner. Part A: On Valley and Mountain Winds III. Dept. of Atmos. Sci., University of Washington, Seattle. AF Contract 19(604)-7201. 203 pp. 1962.
Presented diagrams depicting the temporal and spatial variations of the wind. Concluded, after discussions with A. Defant and H. Hoinkes at Innsbruck, Austria, that the Alps Mountains obviously had an overall anti-wind system of their own which generally negated local Innsbruck anti-winds. When the demarcation between winds and anti-winds was well-defined, the demarcation usually sloped the same way as the valley bottom, but not as steeply. Consequently, the layers increased in thickness from the proximal towards the distal end of valley. Over wet surfaces on a sunny afternoon, the valley wind was only weakly developed probably because of evaporational cooling at the ground. The presence of convective clouds over the valley also caused local currents, which at times overwhelmed the valley wind circulation.

1962 Schultz, H. B. The Interaction of the Macro- and Microclimatic Factors Contributing to the Success of Wind Machines for Frost Protection in Southern California. Biometeorology, S. W. Tromp, ed., p 614-629. Pergamon Press, New York. pp. 614-629. 1962.
Discovered that katabatic winds pulsated and that the katabatic wind layer was about 40 to 50 feet deep.

1962 Frenkiel, J. Wind Profiles over Hills. QJRMS 88:156-169. 1962.
Investigated wind profiles over an isolated hill and a ridge line perpendicular to the prevailing flow. Discovered that there was no close relationship between mean wind profile and the mean temperature profile over hills. While the directional wind profiles were practically uninfluenced by wind speed, they were determined mostly by 1) the hill profile in the immediate neighborhood of the site of measurements; and 2) the hill profile further upwind than the one near the measurement site.

1962 Lawrence, E. N. Atmospheric Pollution (Sulphur Dioxide) in Hilly Terrain. Int. J. Air Wat. Poll. 6:5-26. 1962.

Developed a formula for use in constructing pollution profiles in a rural hilly area surrounded by distant industrial sources. Maximum concentration was frequently found at an intermediate level between the valley bottom and the surrounding hill tops. He suggested that thermal stability had a pronounced effect on observed concentrations, because the wind dispersal effects were reduced.

1962 Baumgartner, A. Die Lufttemperatur als Standortfaktor Am Gr. Falkenstein. Sonderdruck Aus. Forstw. 81:17-47. 1962.

Presented data on daily maximum and minimum temperatures at various heights above ground, at various altitudes, and on various aspects along a slope in the Bavarian Forest.

1962 Myers, V. A. Airflow on the Windward Side of a Large Ridge. JGR 11:4267-4291. 1962.

Developed a model of two-dimensional, laminar flow over a barrier. The model simulated the outflow profile of wind over the crest of the barrier for any given inflow at the foot of the ridge, as well as above the windward slope.

1962 Musaelyan, S. A. Barrier Waves in the Atmosphere. Israel Program for Scientific Translations, Jerusalem. 112 pp. 1964. (Original in Russian was published in 1962.)

Showed vortex developments downwind of the ridgeline and presented a detailed, theoretical discussion of the vertical currents generated by barriers.

1963 Sterten, A. K. A Further Investigation of the Mountain and Valley Wind System in Southeastern Norway. Intern. Rep. K-254. Fursvarets Forsknings-institutt. Norwegian Defense Res. Estab., Kjeller, Norway. 51 pp. 1963.

Investigated the valley wind in the Dokka area of Norway (61¼N) in an open-U valley, its depth being 400 m as compared to a width of 3500 m between valley ridges. He reported that the gradient wind (the wind at the level which is not affected by ground friction, usually 3,000 to 5,000 feet above the surface) generally affected the flow at the ridge before affecting the flow at the valley bottom. When the gradient wind was across the valley, only a moderate-to-strong wind was able to have an effect on the valley floor flow, but when the direction was along the valley, the gradient had almost the same influence at both locations. Using 80 detailed soundings it was concluded that:

1) The mountain wind first appeared in the evening, in a shallow layer near the surface, but increased during the night to dominate the entire valley atmosphere by sunrise.

2) Thereafter, the mountain wind disappeared near the surface, where the conditions became calm, but there still remained a mountain wind above.

3) Shortly afterwards, the valley wind appeared in the calm layer near the ground and thereafter the remaining part of the mountain wind gradually dwindled.

4) In the afternoon, when the mountain wind completely disappeared, the valley wind dominated the entire valley atmosphere.

1963 Davidson, B. Some Turbulence and Wind Variability Observations in the Lea of Mountain Ridges. JAM 2:463:472. 1963.
Investigated the airflow above the lee slopes of a valley in Vermont and reported that the regime showed two phases. Phase I was the wind shadow area just above the lee slope, which had a vertical thickness varying from 50 to 500 m. With strong insolation and weak winds aloft, this area was characterized by upslope winds, particularly near the ground. With stronger winds and strong insolation, the surface winds were directed toward the ridgeline as often as they were directed toward mid-valley. With still stronger overhead winds and cloudly conditions, the wind direction in the Phase I region was mostly toward mid-valley; but the speeds were relatively light compared to speeds in mid-valley at a similar height. Phase II was the connecting area between the wind shadow area and the general flow. This area was characterized by downward vertical velocities and intense horizontal shear. In general, the lower portion of this region was the most turbulent in the valley. The maximum turbulence was generally found to be at 200 to 300 meters above the valley floor or at half the ridgeline height. Under near-inversion conditions the turbulence was much weaker and the area of maximum turbulence was closer to the ridgeline height.

1963 Fuh, Baw-Puf. The Wind Speed in a Valley. Acta Meteorologica Sinica (Peking) 4:518-526. 1963.
Used observations from various countries to conclude that the relative speed of the wind in a valley was dependent upon Angle B, between the wind and the valley, as well as the ratio of the width, L, of the valley to the height, H, of the ridgeline on both sides. The surface wind speed in a valley was greater than that in

open country when Angle B was less than 15° and smaller when the angle was greater than 35¼. Under the former condition, the smaller the angle and the larger the ratio L/H, the more the surface wind speed was strengthened, while under the latter condition, the larger the angle B and the smaller the L/H, the more the wind was diminished. Generally, the minimum speed was found in the morning and evening and the maximum in the afternoon and at night.

1963 Petrosiants, M. A. and Chanysheva, S. G. Some Features of Mountain-Valley Circulation. M. i. G., 9:3-10. 1963.

Examined wind data from a number of valleys in central Asia to determine the effects of dimensions and orientation of the valley on mountain-valley circulations. The time of the onset of mountain and valley winds was related to the length of the valley in the main valleys. In tributary valleys the onset of the winds occurred later. Indicated there was an optimum value of the ratio of the length to width of the valley, favorable for the information of the mountain-valley circulation. Found that the ratio of speed of the valley wind over the length of the valley increased with increasing slope of the valley. Similarly, the ratio of the speed of the mountain wind over the product of the width and length of the valley was found to increase with increasing slope.

1963 Davidson, B. and P. K. Rao. Experimental Studies of the Valley-Plain Wind. Int. J. Air & Wat. Poll. 7:907-923. 1963.

Concluded that nocturnal valley-plain winds were usually downvalley, showed a maximum speed about half way to the ridgeline, increased in intensity with distance downvalley, and frequently dissipated from above.

1963 Tanner, J. T. Mountain Temperatures in the Southeastern and Southwestern United States During Late Spring and Early Summer. JAM 2:473-483. 1963.

Presented a statistical study of the variation of temperature with height along the slopes of two different mountain regions. The regions were relatively moist valleys in the Great Smoky Mountains of Tennessee and the Chiricahua Mountains in a semi-arid region of Arizona. Confirmed the findings of Schell (1934) that the temperature changes at one elevation in the free air were not accompanied by equal changes at the same elevation on the mountainside.

In the valleys of the Smoky Mountains at Sugar-Lands and Oconaluftee (about 108 m in depth), the nocturnal inversions averaged about 350 m in depth while at Le Conte Creek (1475 m in depth), the inversions were 530 m deep. In the

Chiricahua Mountains the inversions were generally about 550 m deep in the 900 m deep valley. In the daytime a capping stable layer usually had a base at about 350 m in Le. Conte Creek Valley and 550 meters in the Chiricahua Mountain Valley.

1964 Buettner, K. J. K., G. Maykut, J. Turner, and J. Zimmerman. Orographic Deformation of Windflow. Washington Univ., Dept. Atmos. Sci. (Contract DA-36-039-SC-89118). 70 pp. 1964.
Discovered that: 1) Particles released on a ridge with a moderate cross-wind tended to travel in a horizontal vortex sheet flow; 2) Most particles with an appreciable settling velocity released on the leeside of the ridge were deposited onto the slop; 3) Particles of a 10-micron size were readily lifted over the ridge; 4) Thermal winds (valley and mountain winds) frequently coexisted with gradient winds. They essentially flowed below the gradient system. With a katabatic thermal wind parallel to the gradient wind, particles released on the ridge split into an upper vortex sheet component and a near surface katabatic component; 5) Lee eddies were rare except for strong wind cases; and 6) The depth of the downslope flow was less than 20 feet in one special study of katabatic flow.

1964 Orville, H. D. On Mountain Upslope Winds. JAS 21:622-633. 1964.
Conducted a numerical study of mountain upslope winds and compared the results of two case studies with each other, with previous studies on an isolated barrier, and with a few observational studies on upslope winds.

1964 Hogstrom, U. An Experimental Study of Atmospherid Diffusion. Tellus 16:205-251. 1964.
Conducted diffusion experiments at two locations in Sweden and developed formulae to calculate downwind ground concentrations. To deal with Studsvik, a site located in complex terrain, a large section of the report examined the influence of topographical discontinuity on diffusion.

1965 Shakina, N. P. A Model of the Development of a Mountain Breeze. Iz. Atmos. & Oc. Phy. 1:262-265. (English Translation).
Presented the results of a numerical simulation of the circulation above an irregularly-heated isolated mountain. Concluded that 1) mountain breezes developed more tempestously than simpler types of local circulation (a slope wind) and 2) the velocity field of a mountain breeze was subject to great variation within the first few minutes of commencement of motion.

1965 Hirota, I. Drag Force Caused by Gravity Waves over a Mountain Barrier. JMSJ 43:116-123. 1965.

Studied internal gravity waves caused by a fluid with a vertical density gradient passing over another fluid. The patterns of gravity waves simulated for the cases of internal Froude Numbers of 0.25, 0.20, and 0.125 compared well with the experimental results obtained by R. Long (1955).

1965 Konyakhina, A. A., M. I. Shaposhnikova, and L. N. Gutman. Effect of Non-Linearity in a Problem of Slope Winds. Iz. Atmos. & Oc. Phy. 1:391-395. (English translation). 1965.

The problem of plane, stationary, non-linear slope winds was reduced by a system of finite-difference equations, which were solved by the M-20 electronic computer using matrix and simple factorization methods together with an interation method.

1965 Buettner, K.J.K. and N. Thyer. Valley Winds in the Mount Rainer Area. Arc. M. Geophy. Biokli. (B) 14:125-147. 1965.

Conducted one of the most extensive studies of mountain-valley flow during four summer seasons. Most of the observations were obtained in the Carbon River Valley which is V-shaped with forested walls sloping at about a 45° angle to a height of 1000 m above the river. There is a glacier at the upper end of the valley (1000 m msl and higher). The authors had insufficient data for a statistical analysis, so they selected examples of phenomena that were frequently observed.

The major effort involved documenting the mountain and valley winds and the anti-winds at higher levels. They showed the diurnal variation of these winds. Generally, there was mountain wind at night, a valley wind in the daytime, and reverse flows at higher levels throughout the day. The mountain and valley wind generally filled the valley to ridge height and the reverse flow had a similar depth. The maximum speed was usually a little below the center of each layer. Overall comparisons of flows showed that well-developed or poorly-developed systems tended to occur simultaneously in all valleys of the area, regardless of their orientation.

1965 Cummings, W. G., M. H. Redfearn and W. R. Jones. Air Pollution by Sulphur Dioxide. Part 1: The Effect of Land Configuration on Pollution by Sulphur Gases. JIF 38:391-405. 1965.

Based on a three-year survey of sulfur dioxide pollution in the complex terrain surrounding the Llynfi Power Station it was concluded that siting a power station in a valley does not necessarily cause increased sulfur dioxide pollution of the nearby high ground.

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1965 Blumen, W. Momentum Flux by Mountain Waves in a Stratified Rotating Atmosphere. JAS 22:529-534. 1965.
Computed the vertical flux of horizontal momentum due to an isolated circular mountain in a rotating atmosphere using Queney's Model and compared results with estimates of frictional stress.

1965 Kasai, T. Studies of Clouds Produced by Low-Level Jets and Mountain Waves. JMSJ 43:196-205. 1965.
Presented results of time-lapse study of mountain wave formation downwind of Hidaka Range on Hokkaido Island, Japan.

1965 Geiger, R. The Climate Near the Ground. Harvard University Press, Cambridge. 611 pp. 1965.
Presented an excellent summary of many investigations of the variation of insolation with time of year, latitude, orientation, and angle of inclination of slopes. Discussed cold air flows at night, and slope and valley winds.

1965 Smith T. B. Diffusion Study in Complex Mountainous Terrain. Meteorology Research Inc. Report to Dugway Proving Ground, U.S. Army Chemical Corps. AD484087. p 106-110. 1965.
Discovered that tracers released high above and upwind of a ridgetop were carried to the lee slope far below the summit under certain stability conditions.

1966 Thyer, N. H. A Theoretical Explanation of Mountain and Valley Winds by a Numerical Method. Arc. M. Geophy. Biokli., A15(3-4):318-348. 1966.
Presented a theoretical model of the local circulation in a V-shaped valley and solved the equations of motion numerically to yield a circulation featuring valley and slope winds, anti-winds, and vertical currents.

1966 Holton, J. R. The Diurnal Boundary Layer Wind Oscillation above Sloping Terrain. Tellus 19:199-205. 1966.
Derived a set of three second-order differential equations which approximately defines the dynamics of the boundary layer and obtained diurnally periodic solutions. Showed that the thermal forcing mechanism accounted for the amplitude of the nocturnal low-level jet observed over the sloping Great Plains region of the United States. However, it appeared that time and height variations in the eddy viscosity and eddy heat diffusion coefficients had to be included to duplicate in detail the vertical structure and phase of the observed jet.

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1966 Khalkechev. V. A. On the Motion of Cold Air Masses in Valleys. Iz. Atmos. & Oc. Phy. 2:199-204. (English translation). 1966.
Investigated the motion of cold air masses in valleys having a complex configuration. Considered the cases of a narrow valley where the influence of the Coriolois force could be neglected and a wide valley where it had to be taken into account.

1966 Smith, M. R. Reduction of Ambient Air Concentrations of Pollutants by Dispersion from High Stacks. In Proc. of the Third National Conf. on Air Pollution, Washington, DC, Dec. 12-14. pp. 151-160. 1966.
Discussed diffusion in complex terrain in general and gave examples at specific sites.

1967 Martin, A. and F. R. Barber. Sulphur Dioxide Concentrations Measured at Various Distances from a Modern Power Station. Atmos. En. 1:655-677. 1967.
Discussed pollutant concentrations observed around a power plant in hilly terrain. Pollution from the 137 m stacks was, on occasion, detected as close as 1 km.

1967 Schroeder, M., M. A. Fosbert, O. P. Cramer, and C. A. O'Dell. Marine Air Invasion of the Pacific Coast: A Problem Analysis. BAMS 11:802-808. 1967.
Presented an extensive review of the literature on airflow over coastal mountains.

1967 Neuberger, H. Vegetation as an Aerosol Filter in Biometeorology II. Proc. Third Intern. Congress. Pergamon Press, Oxford. pp. 639-672. 1967.
Showed that vegetation effectively removed aerosols. (This became known as the "green area" effect.)

1967 Lopez, M. E. and W. E. Howell. Katabatic Winds in the Equatorial Andes. JAS 24:29-35. 1967.
Explained the regular occurrence of a tidal flow of relatively cool air from the Pacific that created a heated katabatic flow down the eastern slopes of the western Andes Mountains and a hydraulic jump.

1967 Thompson, A. H. Surface Temperature Inversions in a Canyon. JAM 6:287-296. 1967.
Reported on the thermal circulations in a small side canyon in the Wasatch Range in northern Utah. The major events of a typical night of radiational cooling were as follows: 1) formation of a thin film of cold air on the floor or the canyon and a short distance up the canyon slopes; 2) rapid shift from up-canyon to down-canyon wind; 3) rapidly increasing wind speed accompanying the continued cooling followed by steady wind the remainder of the night; 4) persistence of

the cold core in the canyon as morning heating progressed; and 5) rapid wind shift from down-canyon to up-canyon in the morning.

The major difference between these conditions and those in larger canyons was that the inversion and nocturnal flow regime began earlier and developed more rapidly in the small canyon.

1967 Foldvik, A. and M. G. Wurtele. The Computation of the Transient Gravity Wave. Geophy. JRAS 13:167-185. 1967.
Presented a pioneering work on the numerical solution of non-linear waves.

1968 Hino, M. Computer Experiment on Smoke Diffusion over a Complicated Topography. Atmos. En. 2:541:558. 1968.
Determined the wind field from the Fickian equation of diffusion to obtain the distribution of smoke concentration. Discovered the computed results were at least as good as wind tunnel results.

1968 Tyson, P. E. Velocity Fluctuations in the Mountain Wind. JAS 25:381-385. 1968.
Concluded that the mountain wind represented a topographically-induced thermodynamic wind of purely local origin able to support eddy energy in the range of frequencies between convective and mechanical turbulence on the one hand, and diurnal and larger-scale circulations on the other.

1968 MacHattie, L. B. Kananaskis Valley Winds in Summer. JAM 7::348-352. 1968.
Discovered, in the north-south Kanaskis Valley that on clear days with weak pressure gradient that surface wind components across the direction of the main valley showed a more pronounced diurnal cycle than components along the valley. The effects of subvalleys on surface winds were less susceptible of being overridden by synoptic scale influences than the flow along the main valley.

1968 Orville, H. D. Ambient Wind Effects on the Initiation and Development of Cumulus Clouds over Mountains. JAS 25:385-403. 1968.
Stated that a mountain dammed the airflow on the upstream side and that heating on the upwind slope created a wave in the airflow upwind. Small perturbations in the potential temperature and water vapor formed at the upwind boundary propagated downwind and became superimposed on the wave.

1968 The Energy Policy Staff, Office of Science and Technology. Considerations Affecting Steam Power Plant Site Selection. U.S. Government Printing Office, Washington, DC. 133 pp. 1968.
This report is exceptionally significant because it represented the most advanced knowledge of the subject by six major governmental agencies. The report did not mention that complex terrain had to be considered in an evaluation.

1968 DeMarrais, G. A., G. L. Downing, and H. E. Meyer. Transport and Dispersion of an Aerosolized Insecticide in Mountainous Terrain. ESSA Research Laboratories Tech. Memo.-ARL-6. Silver Spring, MD. 46 pp. 1968.
Reported on the vertical temperature profiles observed over several tributary valleys and the main drainage valley of the Boise River Valley north of Fairfield, ID. Detected a low-level movement in one direction and anti-wind aloft by observing smoke and low stratus clouds.

1969 Burov, M. I., V. A. Eliseev, and B. A. Novakovsky. Stereo-photogrammetric Method of Studying Atmospheric Diffusion. Tr. GGO, No. 238. 1969.
(Quoted in WMO Technical Note 121, Dispersion and Forecasting of Air Pollution, Geneva, Switzerland, 1972.)
Described a technique for studying diffusion around a 100-m hill by means of stereophotos. The stereophotos were used in pairs and analyzed automatically by means of an accurage stekometre, made by the K. Zeiss firm or by means of a computer.

1969 Goltsberg, I. A. (editor). Microclimate of the USSR. (Translated from Russian for the U.S. Dept. of Commerce by the Israeli Program for Scientific Translations.) Jerusalem. 240 pp. 1969.
Described the use of morphometric indices for graphically describing complex terrain. These indices are an aid in solving applied problems. Also summarized much of the Russian literature on the variation of wind regimes in hilly terrain.

1970 Cramer, H. E., R. K. Dumbauld, and R. N. Swanson. A Computerized Multi-source Diffusion Model for Air Quality Regions with Complex Terrain. GCA Corporation, Salt Lake City, UT. 59 pp. 1970.
Described a computerized multi-source model for use in air quality control regions with complex terrain.

1970 Edinger, J. G., M. H. McCutchan, P. R. Miller, B. C. Ryan, M. J. Schroeder, and J. V. Behar. The Relationship of Meteorological Variables to the Penetration and Duration of Oxidant Air Pollution in the Eastern South Coast Basin. Project Clean Air Research Report #4. Univ. Calif. 64 pp. 1970.
Showed oxidant pollutants were transported beneath the subsidence inversion of the South Coastal Basin to the Conifer Forests of the San Bernardino and San Gabriel Mountains.

1970 National Air Pollution Control Administration and West Virginia Air Pollution Control Commission. Kanawha Valley Air Pollution Study, APTD-41. U.S. Dept. of N.E.W., Raleigh, NC. 367 pp. 1970.
Presented the results of a detailed two-year study of the variation of air pollution in the vicinity of an urban area in a valley bottom. Showed the spatial distribution of a number of pollutants.

1970 Hinds, W. T. Diffusion over Coastal Mountains of Southern California. Atmos. En. 4:107-124. 1970.
Discovered that estimates of vertical diffusion from centerline exposures, crosswind standard deviations and conventional representations of vertical plume growth were not accurate in the mountainous terrain. Diffusion over a system of ridges and canyons usually resulted in lower exposures on the canyon floor than would occur at the same distance over flat terrain, with the average reduction being about 50 percent. Unstable thermal conditions decreased the significance of the terrain while local terrain effects became very significant with stable conditions.

1970 Reiquam, H. An Atmospheric Transport and Accumulation Model for Airsheds. Atmos. En. 4:233-247. 1970.
Developed a mathematical model of the atmosphere in an airshed (large valley). Related pollutant concentrations to pollutant source distributions and intensities and to the volume of air available for dispersion in the Williamette Valley of western Oregon.

1970 Brodine, V., P. P. Gaspar, and A. J. Pallman. The Wind from Dugway. Env. 11:2-9. 1970.
Hypothesized how the release of a poisonous gas at 400 to 500 m above the ground reached a mountainside and killed the sheep grazing in the area (the hypothesis indicated how the plume aloft might readily impinge on slopes downwind from the release point).

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1970 Long R. R. Blocking Effects in Flow over Obstacles. Tellus, 22:471-480. 1970.
Investigated the characteristics of the flow over an obstacle with emphasis on the upstream disturbance which occurred when the obstacle was accelerated in a long water channel.

1970 Rao, P. K. Theoretical Investigations of the Change of Wind Speed along the Axis of a Valley. Arc. M. Geophy. Biokli., Ser. A 19:59-70. 1970.
Investigated the down-valley acceleration of the valley-plain wind under steady-state conditions for short distances along the axis of the valley. Showed that there was a linear relationship between the square of the mean velocity of the valley-plain wind and the distance along the axis.

1971 Stephens, N. T. and R. O. McCaldin. Attenuation of Power Station Plumes as Determined by Instrumented Aircraft. ES&T 5:615-621. 1971.
Examined data from three power plants, two of which were located in complex terrain. Determined pollutant concentration profiles and the half-life of SO_2 in very stable air at distances up to 80 km downwind of a source. (See correspondence in ES&T 6:172-173).

1971 Carpenter, S. B., T. L. Montgomery, J. M. Leavitt, W. C. Colbaugh, and F. W. Thomas. Principal Plume Dispersion Models: TVA Power Plants. JAPCA 21:491-495. 1971.
Summarized 20 years of comprehensive field surveillance and documentation of the dispersion of power plant emissions in complex terrain. Concluded that new formulations were needed for tall stacks because trapping became extremely important with the high level plumes. While the frequency of episodes of high concentrations decreased, the concentrations during the episodes were appreciably greater than those that were predicted by models designed to simulate emissions from short stacks.

1971 Petkovsek, Z. and A. Hocevar. Night Drainage Winds. Arc. M. Geophy. Biokli, Ser. A. 20:353-360. 1971.
Presented a very simple model of drainage winds capable of calculating wind velocities in a cooled layer as a function of the following parameters: net radiation loss, friction coefficient, the angle of the slope, and the lapse rate in the environment above the treated layer. Concluded that the calculated drainage winds matched those observed.

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1971 U.S. Environmental Protection Agency. Mount Storm, West Virginia; Gorman, Maryland; Luke, Maryland; Keyser, West Virginia Air Pollution Abatement Activity. APTD-0656. Air Pollution Control Office, Research Triangle Park, NC. 146 pp. 1971.
Described the results of the investigations of two air pollution problems in complex terrain. One dealt with air pollution damage to commercial tree-growing operations in the mountains and the other dealt with particulate matter and sulfur gases released from industrial plants.

1971 Dames and Moore, North American Weather Consultants, Loren W. Crow, R. G. Larsen, and C. Hill. Joint Meteorological Report Prepared for the Navajo Project, Mohave Project, San Juan Project, Four Corners Project, and Huntington Canyon Project. (Dames & Moore, Atlanta, GA). 87 pp. 1971.
Assembled a unified report concerning the total impact on the environment of the United States by the large coal-fired power plants in the regions. Concluded that 1) based on the consideration of local winds, terrain effects and professional judgment, the Colorado Plateau Region can be divided into specific "air sheds"; 2) evidence indicated little significant meteorological interaction between these air sheds during stagnation; 3) because each major source was located within a different air shed, contaminants from each major source will not interact under stagnation; 4) even when extended periods of stagnation occur, the natural pollutant removal processes of the atmosphere limit the buildup of contaminants; 5) stagnation could last as long as 13 days in the area; and 6) the consequences of the stagnation vary among the different air sheds and plant sites. (See Van der Hoven et al., 1972.)

1972 Miller, P. R., M. H. McCutchan, and H. P. Milligan. Oxidant Air Pollution in the Central Valley, Sierra Nevada Foothills, and Mineral King Valley of California. Atmos. En. 6:623-633. 1972.
Defined oxidant air pollution, temperature, and wind profiles from aircraft measurements conducted several times daily during a two-day period. Evidence of the transport of photochemical smog from the Central Valley to the Mineral King Valley was documented.

1972 Schiermeier, F. A. Large Power Plant Effluent Study (LAPPES). Volume 4 - Instrumentation, Procedures and Data Tabulations (1971) and Project Summary. EPA, Research Triangle Park, NC. 286 pp. 1972.
Described the downwash problem near the Conemaugh Power Plant, located downwind of a ridge near Johnston, PA.

1972 Van der Hoven, I., G. J. Ferber, P. A. Humphrey, G. C. Holzworth, J. L. Heffter, and R. F. Quiring. Southwest Energy Study--Report of the Meteorology Work, Appendix E, NOAA, Washington, DC. 175 pp. 1972.

Described what is now referred to as the NOAA Gaussian Model and the diffusion calculations based on the model for five power plants located in complex terrain (Mohave, Navajo, Four Corners, San Juan and Huntington Canyon). A major difference between this and earlier models was the treatment of plumes during stable conditions. This model assumed that during E and F stable stability conditions, a plume remained at a constant elevation above mean sea level and impacted upon surrounding terrain of equal or greater elevations. The report was prepared in response to a report by power plant consultants. (See Dames & Moore et al., 1971.)

1972 Tyson, P. D., and R. A. Preston-Whyte. Observations of Regional Topographically-Induced Wind Systems in Natal. JAM 11:643-650. 1972.

Presented observation to show the occurrence of boundary layer oscillations in the form of widespread and large-scale topographically-induced mountain-plain and plain-mountain winds over the deeply dissected Eastern Plateau slopes of Natal. By night, advection of cool air from the northwest occurred between the Drakensberg Escarpment Zone and the coast; by day, the flow was reversed and advection from the southeast was characteristic of clear sky conditions. The distinctive temporal and spatial characteristics of the regional winds corresponded in a nearly ideal manner to those expected in a thermodynamically-direct circulation caused by the diurnal cycle of insolation. The mountain-plain wind was fully developed 2 hours before sunrise and was as deep as 1000 m.

1973 Start, G. E., C. R. Dickson, and L. L. Wendell. Diffusion in a Canyon Within Rough Mountainous Terrain. NOAA Technical Memorandum ERL ARL-38. Idaho Falls, ID. 47 pp. 1973.

Discussed three mechanisms which appeared to enhance mechanical turbulence in complex terrain. The first mechanism was the downward transfer of momentum from the turbulence generated around the ridges. The second mechanism occurred during strong temperature inversions when the first mechanism was at a minimum and was a downslope density flow from side of feeder canyons draining into the main canyon with enough momentum to reach the other side of the main canyon. Helical circulations occurred when this flow combined with the downvalley flow in the main canyon. The third mechanism, wake turbulence, occurred where flow over high rough areas caused a cavity in the downwind area. In this cavity there were reduced wind speeds, but increased eddy motion.

1973 Edinger, J. G. Certical Distribution of Photochemical Smog in the Los Angeles Basin. ES&T 7:247-252. 1973.

Explained how pollutants moved up mountain slopes and became embedded in the inversion aloft. On occasion, mixing brought pollution back to the surface.

1973 Fraser, A. B., R. C. Easter, and P. V. Hobbs. A Theoretical Study of the Flow of Air and Fallout of Solid Precipitation over Mountainous Terrain: Part I. Airflow Model. JAS 30 801-812. 1973.

Presented a model for airflow over mountainous terrain. The model indicated that the dynamical effects of latent heat were significant in some cases, but were generally secondary to the barrier effect of the terrain.

1973 Leahey, D. M. and J. Halitsky. Low-Wind Turbulence Statistics and Related Diffusion Estimates from a Site Located in the Hudson River Valley. Atmos. En. 7:49-61. 1973.

Compiled a turbulence climatology for winds speeds ≤ 2 ms^{-1} from bivane measurements at a location in the Hudson River Valley. The method of Hay and Pasquill was employed to quantitate estimates of diffusion.

1973 Hindman, E. E., II. Air Current in a Mountain Valley Deduced from the Breakup of a Stratus Deck. MWR 101:195-200. 1973.

Observed the breakup of a stratus deck in the Redwood Creek Valley in northern California and reported the following: 1) air ascended along the heated slopes; 2) air descended over the center of the valleys; 3) air moved diagonally from the descending air in the mid-valley to the ascending air on the slopes; and 4) the air aloft moved from the ascending flow out to the descending flow in the mid-valley. The magnitude of the upslope flow was 0.14 mps.

1973 Kozhevnikov, V. N. Linerization of the Problem of Flow around a Mountain. Iz. Atmos. & Oc. Phy. 9:320-325. 1973. (English Translation).

Analyzed and compared the flows around the same mountain generated by one linearized and two nonlinear models. Concluded that, in the case of constant temperature and incident-flow velocity gradients, the linearized model of the stationary two-dimensional problem could be used successfully in practical calculations in place of non-linear models.

1973 Walden Research Division of Abcor - Summary Report on Modeling Analysis of Power Plants for Compliance Extensions in 51 Air Quality Control Regions. Cambridge, MA (Prepared for EPA Contract No. 68-02-0049). 74 pp. 1973.
Presented dispersion calculations for many air quality control regions in the eastern United States. Used EPA's Valley Model for power plants in complex terrain.

1973 Nicholls, J. M. The Airflow over Mountains Research 1958-1972. WMO Tech. Note No. 127. Geneva, Switzerland. 74 pp. 1973.
Updated WMO Technical Note No. 34 (see Queney et al., 1960) and emphasized large-scale and lee wave phenomena.

1974 Manabe, S. and T. B. Terpstra. The Effects of Mountains on the General Circulation of the Atmosphere as Identified by Numerical Experiments. JAS 31:3-42. 1974.
Presented model results indicating that 1) mountains markedly increased the kinetic energy of stationary disturbances by increasing the stationary component of the eddy conversion of potential energy, while they decreased the kinetic energy of transient disturbances and 2) the probability of cyclogenesis increased significantly on the lee side of major mountain ranges where the core of the westerly jet was located.

1974 Leslie, L. M. and R. K. Smith. A Numerical Simulation of Katabatic Winds and Their Effect on Pollution Dispersal in Urban Areas. Proc. 5th Australian Conf. Hydraulic Fluid Mechanics, Univ. of Cantaberra, Christchurch, N.Z. Vol. 2, pp. 553-560. 1974.
Investigated numerically the effectiveness of katabatic circulations in dispersing an atmospheric pollutant, but did not compare results with field observations.

1974 Leahey, D. M. and R. D. Rowe. Observational Studies of Atmospheric Diffusion Processes over Irregular Terrain. Paper #74-67 presented at APCA Annual Meeting, Denver, CO, June 9-13. 22 pp. 1974.
Collected wind data with tetroons, helicopters, and bivanes in order to study the airflow over a mountain valley, over a long two-dimensional ridge, and over a river bank. The airflow behavior was very different for each of the topographic features. Diffusion coefficients were derived for each feature and found to be appreciably larger than what the the Pasquill classification technique indicated.

1974 Kao, S. K., H. N. Lee, and I. I. Smidy. A Preliminary Analysis of the Effect of Mountain-Valley Terrains of Turbulence and Diffusion. AMS - Second Atmos. Diffusion Conf. pp. 59-63. 1974.

Presented analyses of the wind data recorded at 15 surface stations in the Salt Lake Valley. Showed the streamline patterns and the distribution patterns of the kinetic energy of the mean and turbulent motion for different times of the day and seasonal differences in eddy diffusivity.

1974 Egami, R. T., V. Sharma, R. L. Steele, and P. E. Testerman. Diffusion Study in the Vicinity of Mohave Generating Plant. AMS - Second Atmos. Diffusion Conf. pp. 209-213. 1974.

Presented a few case studies of the vertical variation of winds and temperatures in the Colorado River Valley in the vicinity of the Mohave Plant. The wind directional pattern did appear complex, but there was evidence of flow in the valley and anti-winds aloft both during the day and night. Concluded 1) the continuous Aitken particle counter was a practical tool for defining the mixing layer and was superior to the temperature sounding; 2) the use of a chemiluminescent-type ozone monitor showed promise for plume tracking; and 3) the analysis of wind fields in rough terrain demonstrated that constructing a dispersion model for complex terrain was difficult. Presented evidence of two widely-separated peaks (the upper peak may have been aged pollution and the lower peak new pollution.

1974 Hovind, E. L., T. C. Spangler, and A. J. Anderson. The Influence of Rough Mountainous Terrain on Plume Dispersion from an Elevated Source. AMS - Second Atmos Diffusion Conf. pp. 214-217. 1974.

Reported results from field studies at three separate sites in the southwestern United States to illustrate the effect of terrain roughness upon plume dispersion from an elevated source. One site was relatively smooth, but did include some low bluffs and cliffs in the direction of rising terrain. The second site was relatively open with considerable ground roughness. The third site was a canyon with a gradually rising floor and steep canyon walls. Quantitative assessments of plume dispersion were based either on aerial measurements of oil fog plume centerline measurements or on the quantitative impact of a tracer upon the sampling network in the surrounding elevated terrain. Comparing calculated concentrations to observed concentrations it was found that 1) at the smooth site, there was good agreement; 2) at the rough site the calculated concentrations were generally too high by a factor of six; and 3) at the canyon site the calculated concentrations were too high by a factor of 10.

1974 MacCready, P. B., Jr., L. B. Baboolal, and P.B.S. Lissaman. Diffusion and Turbulence Aloft over Complex Terrain. AMS - Second Atmos. Diffusion Conf. pp. 218-225. 1974.

Reported on the results of a field experiment of plume dispersion during stable conditions with a weak katabatic flow. Concluded that the categorization schemes of turbulence and diffusion of the Pasquill-Gifford-Turner type and NRC Safety Guide 23 show less dispersion during stable conditions in complex terrain. Stated, "In the weak, katabatic drainage flows, a stable temperature gradient is associated with turbulence, just opposite to the normal assumption."

1974 Start, G. E., C. R. Dickson, and R. R. Ricks. Effluent Dilutions over Mountainous Terrain and Within Mountain Canyons. AMS - Second Atmos. Diffusion Conf. pp. 226-232. 1974.

Investigated effluent dilution within a canyon and impaction on the canyon walls. Found that during weak lapse conditions, effluent dilution in the canyon was almost 4 times greater than that predicted using Pasquill stability categories. With neutral conditions, the dilution was 5 times greater and during very stable conditions 15 times greater than that indicated by the Pasquill technique. Enhanced mechanical turbulence was believed to be the cause of greater dilution in the canyon area. The authors indicated that the plume impacted on canyon walls during lapse conditions, but said nothing about impaction during stable conditions.

1974 Giroux, H. D., L. E. Hauser, L. H. Teuscher, and P. E. Testerman. Power Plant Plume Tracing in the Southern California Marine Layer. AMS - Second Atmos. Diffusion Conf. pp. 238-245. 1974.

Studied plume movement by injecting sulfur hexafluoride (SF_6) into the flue gases and detecting the tracer using portable gas chromatographs with electron capture detectors. Four-hour bag samples were collected at each of 27 fixed monitoring stations on the Oxnard Plain (Ventura County, CA) and its periphery. The major conclusions were 1) the vertical structure of the plume was clearly defined and the plume generally remained between ground level and the inversion base; 2) the plume trajectory changed in concert with changes in wind direction; 3) ground level tracers of the plume were found as far as 40 km with primary impact occurring within 25 km of the source; 4) there were no significant differences between concentrations measured over elevated terrain directly in the plume path and those measured over the surrounding flatlands; and 5) there was no observed buildup of background concentrations due to the back-and-forth motion associated with the alternative land and sea breezes.

1974 Roffman, A. and R. Grimble. A Time-Dependent Air Quality Model with Terrain Corrections. AMS - Second Atmos. Diffusion Conf. pp. 311-316. 1974.
Developed a three-dimensional, time-dependent model to predict concentration distribution of various pollutants emitted from fossil-fueled electric generating power plants. The model accounted for terrain features, variations in wind and diffusivity profiles, and mixing depths. No model validation was included.

1974 Lin, J., H. Liu, V. Pao, D. K. Lilly, M. Israezi, and S. A. Orzag. Laboratory and Numerical Simulation of Plume Dispersion. EPA-650/4-74-044, USEPA, Research Triangle Park, NC. 76 pp. 1974.
Concluded that stably stratified flow upstream of the "mountain ridge" was blocked and that the plume rise and spread increased. In one experiment a significant amount of pollutant was trapped in the semi-stagnant region just upstream of and below the mountain ridge. The flow more frequently was around rather than over the obstacle; the lateral spread increased considerably; and the vertical spread was reduced. With higher Froude numbers, pollutants downstream of the obstacle were carried closer to the surface by the downslope flow.

1975 Klemp, J. B. and D. K. Lilly. The Dynamics of Wave-Induced Downslope Winds. JAS 32:320-339. 1975.
Derived a theory for the dynamics of strong surface winds on the lee side of a large mountain range and compared the theory with observations. The observed strong winds were found to be surface manifestations of standing resonant lee wavelengths. Comparisons of the model simulations with observations were favorable.

1975 Drazin, P. G. and C. H. Su. A Note on Long-Wave Theory of Airflow over a Mountain. JAS 32:437-439. 1975.
Proved that the effects of the atmospheric structure and the mountain profile on lee waves can be determined separately assuming small perturbations, long wavelengths, and two dimensionality. The flow was described by a composite formula.

1975 Mahrer, Y. and R. A. Pielke. A Numerical Study of the Airflow over Mountains Using the Two-Dimensional Version of the University of Virginia Mesoscale Model. JAS 32:2144-2155. 1975.
Adopted the University of Virginia mesoscale model to study airflow over a mountain. Included improvements suggested by Deardorff. The results of two sets of experiments were studied and compared to the results of other other models and to field observations.

1975 Air Monitoring Center, Rockwell International. Vol. 1. Final Program Report. Navajo Generating Station Sulfur Dioxide Field Monitoring Program. 602 pp. 1975.
Reported on a cooperative investigation involving six governmental and private utility organizations. The major purpose of the investigation was to evaluate the need for SO_2 removal at the Navajo generating station. The principal conclusion of the study was that in the course of the life of the Navajo generating station, the frequency of exceeding a three-hour average SO_2 concentration of 1300 $\mu g/m^3$ was less than twice per year. Dispersion conditions surrounding the plant were evaluated in terms of observed quantities. The highest concentrations occurred in the sector which included Leche-e-Rock and the Vermillion Cliffs and were attributed to ground-level impact at the sides and tops of these two high terrain locations.

1975 U. S. Environmental Protection Agency. Intercomp Resources Development and Engineering, Inc. Evaluation of Selected Air Pollution Dispersion Models Applicable to Complex Terrain. EPA-450/3-75-059. USEPA, Office of Air Quality Planning and Standards, Research Triangle Park, NC. 96 pp. 1975.
Compared the result of the Intercomp, EPA and NOAA complex terrain models. Concluded that the Intercomp model was most accurate and that the EPA and NOAA models over-predicted.

1975 Seinfeld, J. H. Air Pollution - Physical and Chemical Fundamentals. McGraw-Hill Book Co., New York. pp. 260-264. 1975.
Presented two- and three-dimensional dispersion equations for predicting plume concentratons in complex terrain.

1976 Riley J. J., H. T. Liu, and E. W. Geller. A Numerical and Experimental Study of Stably Stratified Flow Around Complex Terrain. EPA-600/4-76-021. USEPA, Research Triangle Park, NC. 31 pp. 1976.
Developed a computer program to compute three-dimensional, stratified flow around complex terrain for the case of very strong stratification. Performed laboratory experiments for stratified flow past three different terrain models. Preliminary comparisons indicated that the computed results were in fair agreement with the experiment.

1975 Jackson, P. S. and J.C.R. Hunt. Turbulent Flow over a Low Hill. QJRMS 101:929-955. 1975.
Presented an analytical solution for the flow of an adiabatic turbulent boundary layer on a uniformily rough surface over a two dimensional hump with small curvature (a low hill). Some comparisons of actual winds and wind tunnel flows were made. These suggested that the theory may be useful in approximating the effect of hills on the wind.

1976 Start, G. E., N. R. Ricks, and C. R. Dickson. Effluent Dilutions over Mountainous Terrain. AMS - Third Atmos. Diffusion Conf. pp. 407-414. 1976.
Investigated atmospheric dispersion to the north and over the Oquirrh Mountains near Garfield, Utah. Concluded that 1) elevated plume-centerline concentrations appeared to be suitably predicted by the Pasquill-Gifford dispersion parameters when the airborne effluents did not flow across the mountainous terrain; 2) elevated plume-centerline concentrations measured over the rough terrain averaged two to four times more dilution than that predicted for smooth terrain (much of this was due to plumes being deflected laterally when attempting to flow out and around the blocking obstacles and the rest was due to the vertical shearing of wind direction with height): 3) the locations of maximum ground-level plume concentrations were predicted best by pibal observations near the effective plume height; and 4) the physical setting and topography of a particular size appeared to have a considerable effect on the observed atmospheric dilution.

1976 Williams, M. D. and R. Cudney. Predictions and Measurements of Power Plant Plume Visibility Reductions and Terrain Interactions. AMS - Third Atmos. Diffusion Conf. pp. 415-420. 1976.
Determined a relationship using concentrations determined through samplers mounted on aircraft, between pollutants and visibility enabling one to calculate plume opacities and visual range reductions. Concluded, with no ground observations, that power plant plumes readily and directly impacted on distant high terrain at the effective stack height of the plume.

1976 Roffman, A., T. P. Kapsha, P. E. Kueser, G. L. Bethune, and M. P. Sullivan. A Field Study on the Behavior of a SO_2 Plume from a Power Plant Near Complex Terrain and Under Stable Atmospheric Conditions. AMS - Third Atmos. Diffusion Conf. pp. 421-429. 1976.
Conducted via aircraft a plume tracking study in the vicinity of the Tracy Station Power Plant in complex terrain 20 km east of Reno, Nevada. Concluded that 1) the models, generally used by regulatory agencies to determine the potential impact of the power plant plume

for stable atmospheric conditions and elevated terrain, yielded concentrations that were too high by a factor ranging from 6.2 to 11.2 (average of 8.7); 2) the increase in plume dilution under stable conditions and near elevated terrain was most likely due to increased spreading in both the horizontal and vertical; and 3) under stable conditions and very light winds speeds (<0.5 mps), plume meander, which exceeded 180° on many occasions, was not considered by the regulatory agencies.

1976 Clements, W. E. and S. Barr. Atmospheric Transport and Dispersal at a Site Dominated by Complex Terrain. AMS - Third Atmos. Diffusion Conf. pp. 430-435. 1976.

Studied the temporal and spatial variation of the nocturnal drainage wind in a canyon-mesa area at Los Alamos, NM. On the mesa top, the slope wind was typically 1-2 mps and subject to transient wind interruptions. Within the canyon the mean flow was weaker (0.5-1.0 mps), but was extremely steady and readily identifiable. Drainage was more pronounced in winter than in summer. Using tracers, it was found that the canyon flow responded to a separate but similar set of driving forces from the mesa-top drainage; the response to a change in heat was sooner in the canyons. A mesa-top cross-canyon component of 2 mps or more produced separated flow and a major roll eddy within the canyon in stable conditions. The consequence of this phenomenon was vigorous mixing of the air within the canyon and extensive canyon-mesa air exchange.

1976 Bowers, J. F., Jr. and H. E. Cramer. Comparison of Calculated and Observed Characteristics of Plumes from Two Coal-Fired Power Plants Located in Complex Terrain. AMS - Third Atmos. Diffusion Conf. pp. 463-469. 1976.

Presented a short-term diffusion model and concluded that aircraft measurements of the characteristics of the stack plumes of two power plants in complex terrain in West Virginia confirmed accuracy of the model, which considered entrainment effects prior to plume stabilization. Results generally showed that the horizontal and vertical spreading of plumes was in good agreement with model predictions.

1976 Fox, D. A., M. A. Fosberg, W. E. Marlatt, and W. Reeser. Analysis of Mountain Air Quality. AMS - Third Atmos. Diffusion Conf. pp. 470-475. 1976.

Outlined a procedure for calculating temperature, winds, and dispersion in mountainous terrain. The procedure was designed to provide a qualitative estimate of the meteorological factors involved in land management decisions. The authors stated that the procedures required a minimum of expense and data yet provided what appeared to be a

reasonably accurate assessment of the air quality impact of activities in mountainous terrain.

1976 Lantz, R. B., G. F. Hoffnagle, and S. B. Pahwa. Diffusion Model Comparisons to Measured Data in Complex Terrain. AMS - Third Atmos. Diffusion Conf. pp. 476-483. 1976.

Used diffusion data from three areas in mountainous terrain to compare models developed by NOAA, EPA, and INTERA. Concluded it was necessary to consider the expected wind flow in order to make reasonable predictions of ground-level concentrations in complex terrain environment. Found that the NOAA model underestimated concentrations in unstable cases and overestimated them in stable cases. The EPA model was slightly better in stable conditions, but poorer in unstable cases. The INTERA model, according to the authors, produced the best results.

1976 Egan, B. A. and A. Bass. Air Quality Modeling of Effluent Plumes in Rough Terrain. AMS - Third Atmos. Diffusion Conf. pp. 484-487. 1976.

Concluded that more field studies were needed and that emphasis should be placed on plume geometry, rather than assuming homogeneity of the flow field.

1976 Kao, S. K. A Model for Turbulent Diffusion over Complex Terrain. JAS 33:157-158. 1976.

Constructed a model, which considered the half-life of a pollutant, for turbulent diffusion over complex terrain. Did not compare results with field observations.

1976 Paegle, J. N. and J. Paegle. Frequency Spectra of Atmospheric Motions in the Vicinity of a Mountain Barrier. JAS 33:499-506. 1976.

Computed frequency spectra of heights and geostophic vorticities for several points over the western continental United States and Eastern Pacific. These spectra exhibited variations which appeared to be at least partially attributable to the underlying topography.

1976 Smith, R. B. The Generation of Lee Waves by the Blue Ridge. JAS 33:507-519. 1976.

Described a study of the flow over a low, straight section of the Blue Ridge Mountains in the central Appalachians. Compared field observations with laboratory experiments to improve an existing model.

1976 Davis, B. L., D. N. Blair, L. R. Johnson, and S. J. Haggard. A Study of the Green Area Effect in the Black Hills of South Dakota. Atmos. En. 10:363-370. 1976.
Used bimonthly sampling of Aitken and larger particles for a twelve-month period in the Black Hills of South Dakota and showed several possible particle removal mechanisms. Concluded that the "green area" effect might reduce ambient Aitken particle concentrations by as much as 50%,

1976 Weir, A., Jr., D. G. Jones, L. T. Papay, S. Calvert, and C. Yung. Factors Influencing Plume Opacity. ES&T 10:539-544. 1976.
Conducted parametric investigations of the effects of independent variables on plume opacity using light scattering theory at the Mohave Power Plant at South Point, Nevada. Showed that plume opacity varied as much as 14 to 87% depending only on the geographic location of the source and the time of day.

1976 Wilson, R. B., G. E. Start, C. R. Dickson, and N. R. Ricks. Diffusion under Low Windspeed Conditions near Oak Ridge, Tennessee. NOAA Technical Memorandum ERT ARL-61. Idaho Falls, ID. 83 pp. 1976.
Studied dispersion when the winds were light and meandered considerably. Discovered that vertical mixing was enhanced to almost the same degree as horizontal dispersion by the meander. Although Pasquill never recommended the use of his technique when routine measurements indicated calm conditions, the investigators reported that 1) the standard deviation of the lateral plume spread, σ_y, averaged 5.7 times greater than predicted values. Ground reflection may have contributed to the enhanced vertical diffusion.

1976 Merkine, L. and E. Kalnay-Rivas. Rotating Stratified Flow over Finite Isolated Topography. JAS 33:908-922. 1976.
Analyzed inviscid, steady, stratified rotating flow over a finite, isolated topographic feature. The formulation was based on approximating the horizontal momentum by the the geostrophic momentum.

1976 Blumen, W. and C. D. McGregor. Wave Drag by Three-Dimensional Mountain Lee Waves in Nonplanar Shear Flow. Gellus 28:287-298. 1976.
Considered the effect of both cross-wind and vertical shear of the basic flow in a linear, hydrostatic model of stationary, mountain lee waves on a stably stratified airstream near an isolated hill. Determined analytical solution for a constant lapse rate basic-state.

1976 Tang, W. Theoretical Study of Cross-Valley Wind Circulation. Arc. M. Geoph. Biokli., Ser. A 25:1-18. 1976.
Developed an analytical model to investigate the interaction between the large-scale air flow and thermally-induced wind circulation. The Boussinesq approximation was assumed. The lower order successive solutions were obtained in spectral representation for both typical daytime and nighttime cases. The results produced circulation features often observed in mountainous terrain.

1977 Koch, R. C., W. G. Biggs, P. H. Hwang, I. Leichter, K. E. Pickering, E. R. Sawdy, and J. L. Swift. Power Plant Stack Plumes in Complex Terrain. EPA-660/7-77-020. ESRL, Research Triangle Park NC. 236 pp. 1977.
Presented a fairly extensive review of 16 field investigations of dispersion in complex terrain. Discussed contrary and consensus views on airflow, turbulence, and diffusion phenomena. General conclusion was that all state-of-the-art models of transport and diffusion of continuous elevated plumes in complex terrain were in their initial stages of development; much more validation data were needed.

1977 Whaley, H. and G. K. Lee. Plume Dispersion in a Mountainous River Valley During Spring. JAPCA 27:1001-1005. 1977.
Found that the plume axis elevations were generally lower during stable and neutral conditions than those predicted by Briggs' plume-rise formulae. In contrast, plume dispersion, although confined in the horizontal by the steep valley walls during both stability regimes, was significantly enhanced by vigorous lateral mixing, particularly close to the source.

1977 Haussling, H. J. Viscous Flows of Stably Stratified Fluids over Barriers. JAS 34:589-602. 1977.
Used a numerical technique and a model to demonstrate the transition of a viscous flow over an infinitely long barrier from homogeneous to stably stratified conditions. Even at low Reynolds numbers the transition was similar to that predicted by inviscid models. However in the homogeneous case, the potential flow of the invisid flow was replaced by a flow with separation and recirculatory regions adjacent to the ridge.

1977 Clark, T. L. and W. R. Peltier. On the Evolution and Stability of Finite-Amplitude Mountain Waves. JAS 34:1715-1730. 1977.
Described a series of fixed Froude number numerical simulations of the generation of internal gravity waves by the flow of stably stratified fluid over an isolated obstable.

1977 Chung, Y. S. An Observational Study of the Influence of Large-Scale Mountains on Airflow and Lee Cyclogenesis. Arc. M. Geoph. Biokli., Ser. A 26:109-126. 1977.

Observed significant large-scale topography-induced orographic modifications in upper airflows. Only 14 to 26% of upper cold lows crossed major mountain systems, while the remainder passed major mountain systems as cold troughts. In the course of prolonged upslope motions over a chain of mountains, upper-level contours fanned out laterally due to the generation of orographic mass-divergence, increased friction, etc.

The upper-level flows over the Massifs, the Andes, the Rockies, and the East Asian Mountains tended to be weaker than those observed upstream and downstream, which is contrary to many numerical/physical models. Examination indicated that the decrease of wind flows was associated with orographic vertical motions, horizontal divergence and deflection, vertical shrinking, increased friction, and blocking and splitting flows in the large-scale mountains.

1977 Fabrick, A., R. Sklarew, and J. Wilson. Point Source Model Evaluation and Development Study. Radian Corporation, Austin, TX. 197 pp. (no date; probably 1977.)

Presented the results of a study of the comparative attributes of air pollution point source submodels, which were tested against four data bases and analytic solutions. Concluded that the grid-type model was superior to the Gaussian model in terms of precision, realism, and generality. Noted that the Gaussian model was not applicable to complex terrain situations where high wind shear and strong inversions can result in plume channeling and other effects that produce non-Gaussian concentration profiles. Stated, "After careful review of the Gaussian evaluation tests, one reaches the conclusion that almost any desired result can be obtained, given the range of options for the dispersion parameters, plume trajectory in complex terrain, etc., and the range of uncertainty in the observed wind speed, wind direction, and atmospheric stability."

1977 Swolik, A. A., J. M. Austin, and G. N. Pica. Plume Dispersion Modeling in Complex Terrain under Stable Atmospheric Conditions. Presented at APCA Annual Meeting, June 20-24, 1977, Toronto, Canada. 16 pp. 1977.

Summarized data from a large field program involving a power plant effluent study (LAPPES) and compared observed SO_2 concentrations with those predicted by two commonly-used models. Proposed a new model (see Schiermeier, 1972).

1977 Cabe, D. B., B. R. Eppright, Jr., and J. D. Stuart. Application of the Gaussian Dispersion Model to Predicting Maximum Plume Concentrations in Abruptly Rising Terrain. Presented at APCA Annual Meeting, June 20-24, 1977, Toronto, Canada. 15 pp. 1977.

Demonstrated that the steady-state Gaussian model, modified to ignore contributions from ground-based reflections, was a useful tool in prediction of maximum ground-level concentrations resulting from plume impaction on abruptly rising terrain. Discovered that the model performed well when the concentrations were high, but poorly when the concentrations were very low.

1977 Kao, S. K. and G. H. Taylor. Effect of Mountain Terrain on Diffusion in the Planetary Boundary Layer. AMS-APCA Joint Conf. pp. 119-125. 1977.

Investigated the effect of mountains on dispersion using a major SO_2 source (smelter) located at the north end of the Oquirrh Mountains, approximately 15 miles west of Salt Lake City, UT. The SO_2 sampling was limited to observations by aircraft. They found that the σ_y's calculated from experimental results exceeded those predicted by the model for diffusion over a flat surface for extremely unstable (Class A) situations, despite the fact that actual conditions were quite stable. The vertical dispersion parameter, σ_z, however, was approximated fairly well by the predictive equations. They further concluded that there was a considerable amount of turbulence downwind of an obstacle. (Turbulence can readily occur over smooth terrain many km downwind of an obstacle.)

1977 Nappo, C. J., Jr. Horizontal Variability of Mesoscale Winds over Complex Terrain. AMS-APCA Joint Conf. pp. 140-145. 1977.

Examined wind data to determine the horizontal variability of the mesoscale flow over complex terrain in eastern Tennessee. Found that horizontal variability on a scale of 100 km was minimal during unstable conditions and great during stable conditions.

1977 Elliott, R. D., E. L. Hovind, and M. W. Edelstein. Observations and Model Calculations of Plume Impaction on Rising Terrain. AMS-APCA Joint Conf. pp. 182-187. 1977.

Proposed changes for the Gaussian plume dispersion models for complex terrain. The basis for the recommended changes was that plume movements over complex terrain were different than those over smooth ground. The authors reported that air accelerated while passing over a ridge and that the embedded plume underwent vertical shrinking and downwind stretching. The authors further claimed that preservation of mass continuity in the vertical required the plume centerline to follow a streamline that did not touch the ground. In the absence of a change in turbulence, the ground

level concentration remained essentially the same in the plume that was disturbed by flowing over a ridge as in one not as disturbed. The NAWC mixing model was proposed as an improvement over the smooth terrain model. A table summarizing data from 13 field experiments showed that the smooth terrain model always overpredicted (3 to 50 times).

1977 Huffnagle, G. F., B. A. Egan, and B. R. Greene. Application of Models in Complex Terrain. AMS-APCA Joint Conf. 196-203. 1977.
Reviewed the requirements for a model in complex terrain. Analyzed data from western Pennsylvania and concluded that models perform well when they include 1) buoyancy entrainment to provide initial spreading of the plume; 2) modification of the plume path to account for lift created by the obstacle; and 3) greater diffusion coefficients to account for the surface roughness and the resultant turbulent energy.

1977 Mullen, J. B., M. W. Chan, and I. H. Tombach. Development and Valiation of a Model for Diffusion in Complex Terrain. AMS-APCA Joint Conf. pp. 188-191. 1977.
Presented the Aerovironment Multi-Source Terrain Model (AVMSTM), a steady-state model which assumed uniform meteorology and was subject to the limitations of over-response under conditions of rapidly changing meteorology. In spite of these limitations, AVMSTM was a useful tool for assessing the effect of changing source configurations and for identifying conditions which produce the highest impacts. The model proved to be valid even with data averaged over an hour.

1977 Burt, E. S. and H. H. Slater. Evaluation of the Valley Model. AMS-APCA Joint Conf. pp. 192-195. 1977.
Reported that at four of six sites on mountainous terrain near the height at which plumes from major facilities stabilize, the valley model calculated maximum 24-hour SO_2 concentrations within a factor of 2 of the second-highest observed concentrations. (At the other sites there were overpredictions of concentrations by factors of 5 to 10.)

1977 Yocke, M. A. and M. Liu. The Development of a Three-Dimensional Wind Model for Complex Terrain. AMS-APCA Joint Conf. pp. 209-214. 1977.
Developed a three-dimensional model for the simulation of wind fields over rugged terrain. The model, based upon mass continuity, was composed of several horizontal layers of varying thicknesses. The model results compared favorably with observational data.

1977 Sklarew, R. C., J. C. Wilson, and A. J. Fabrick. Depict/ Impact Grid Models of Reactive Point Source Emissions in Complex Terrain. AMS-APCA Joint Conf. pp. 215-220. 1977.
Developed a model to calculate the total problem of impaction of reactive source emissions in complex terrain. Concluded, after applying data from a brief sampling period, that the model was very useful and versatile. A plea was made for representative field data and for assessing accuracy of the field data when disagreement occurred between the model and the data.

1977 Lange, R. and C. A. Sherman. Particle-In-Cell vs. Straight Line Gaussian Calculations For an Area of Complex Topography. AMS-APCA Joint Conf. pp. 225-231.
Analyzed the differences between calculations of time-integrated air concentrations and ground depositions for the standard straight-line Gaussian plume model and the three-dimensional time-dependent PIC model (Atmospheric Diffusion Particle-In-Cell) for the Hudson River Valley. Discovered 1) the calculations differed greatly, 2) the Gaussian methods calculated higher concentrations under stable conditions, and 3) the PIC method calculated concentrations over larger areas, because of its consideration of meandering and secondary exposure from the returning plume after flow reversal.

1977 Lavery, T. F. and L. L. Schulman. The Validity of a Gaussian Plume Point Source Diffusion Model for Predicting Short-Term SO_2 Levels in the Vicinity of Electric Generating Plants in New York State. AMS-APCA Joint Conf. pp. 291-298. 1977.
Described a Gaussian point source diffusion model which was used to predict hourly, 3-hourly, and 24-hourly averaged SO_2 concentrations in the vicinity of four electric generating plants in New York State. The ratios of the predicted to maximum observed concentrations exhibited a large variance for all stability regimes.

1977 Wilson, D. A., H. E. Cramer, J. F. Bowers, Jr., and H. V. Geary, Jr. Detailed Diffusion Modeling as a Method for Interpreting and Supplementing Air Quality Data. AMS-APCA Joint Conf. pp. 315-320. 1977.
Performed a detailed and systematic analysis using concurrent emissions, meteorological and air quality data in complex terrain. Demonstrated the capability of the modeling techniques to yield both short-term and long-term concentration estimates in close agreement with air quality observations.

1977 Burt, E. Valley Model User's Guide EPA-450/2-77-018. USEPA, Research Triangle Park, NC. 122 pp. 1977.
Presented the Valley Model, which estimates the upper limits of 24-hour pollutant concentrations due to sources in rural, complex terrain. The options allow multiple sources, flat terrain, urban areas, and long-term averages to be considered.

1977 Hovind, E. L., T. C. Spangler, N. E. Graham, and P. G. Sagert. Valley Circulation Influence on Tall Stack Dispersion from a Ridge Location. Presented at NATO/CCMS meeting on Air Pollution Modeling and Its Application. August 28-31, 1977, Toronto, Canada. 10 pp.
Studied SF_6 oil fog dispersion in the north-south oriented valley in the Upper Hat Creek. (The valley was about 5-10 km wide with a northward drainage and the valley ridges were 600 to 1000 m above the valley floor.) There were 14 tracer releases during the winter, spring, and summer of 1976. The major conclusion was that a very complicated valley-slope circulation existed. The highest concentrations tended to occur on the western slopes and were attributed to fumigation accompanying cross-valley flows.

1977 Benjamin, S. F., J. J. Havlena, and R. D. Rowe. Observational Studies of Air Quality and Air Flow Over a Ridge Downwind of a Stack. Presented at APCA Annual Meeting, June 20-24, 1977, Toronto, Canada. 16 pp.
Analyzed observations of wind and SO_2 concentrations at two sites along the top of a ridge downwind of a sour gas plant. At the site nearest the plant, the highest concentrations were associated with high winds and neutral thermal stability, whereas, at the more remote site, light winds during stable conditions produced the worst pollution. The high concentrations during stable conditions were associated with the horizontal deflection of the streamlines as they approached the ridge.

1977 Cramer, H. E., J. F. Bowers, and H. V. Geary. Comparison of Calculated Observed Ground-Level SO_2 Concentrations for the ASARCO-Tacoma Copper Smelter. Presented at APCA Annual Meeting, 1977, Toronto, Canada. 14 pp.
Demonstrated that existing diffusion-modeling techniques were capable of providing accurate estimates of short-term ground-level SO_2 concentrations produced by emissions from a tall stack located in complex terrain.

1977 Whiteman, C. D. and T. B. McKee. Observations of Vertical Structure in a Deep Mountain Valley. Arc. M. Geophy. Biokli., Ser. A 26;39-50. 1977.

Showed from observations using a tethered balloon sounder in the Gore River Valley of western Colorado that on a clear morning, an inversion top descended at a steady rate of 120 m h^{-1}. Weak down-valley winds were present within the inversion layer while stronger up-valley winds prevailed above (see Pollak, 1924 and Ayer, 1961).

1977 Kitabayashi, K. Wind Tunnel and Field Studies of Stagnant Flow Upstream of a Ridge. JMSJ 55:193-203. 1977.

Studied stagnant flow appearing upstream of a ridge under stable regimes by observing winds and by a wind tunnel experiment. Stagnant flow formed with the nocturnal inversion and disappeared when the inversion disappeared. The critical Froude number above which the stagnant flow disappears, was estimated to be about 2.3.

1977 Furukawa, T. Part 1. Numerical Experiments of Air Flow Over Mountains. Part 2. Some Comparisons of Linear and Nonlinear Treatment of the Equation System and Lower Boundary Condition. JMSJ 55:325-330. 1977.

Discussed the physical relations among four cases, i.e., combinations of two equation systems (linear and nonlinear forms) and two boundary conditions (linear and nonlinear). The nonlinear interactions between the disturbances and the 1) weakening of the approaching flow in the lowest layer ahead of the mountain; 2) generation of the strong wind zone near the level of the mountain crest; 3) intensification of the downslope winds; and 4) extension of the strong winds far downstream in the lowest layer.

1977 Fabrick, A., R. Sklarew, and J. Wilson. Point Source Model Evaluation and Development Study. Science Applications, Inc., Westlake Village, CA. 197 pp. 1977.

Presented the results of an investigation of the attributes of air pollution point source submodels. The submodels were tested against field data bases as well as analytic solutions. The submodels were divided into two classes: a generalized Gaussian model, Gaussian Evaluation Model (GEM) and a finite difference model, Integrated Model for Plumes and Atmospherics in Complex Terrain (IMPACT). GEM permits the user to specify options for each of the major parameters (i.e., horizontal and vertical dispersion, standard deviations, plume rise, terrain characteristics, and mixing height). An extension of GEM was developed to automatically calculate concentrations over an array of receptors and was called GEMGAR (GEM with Gridded Array of Receptors).

1978 Fabrick, A. User Guide to IMPACT: An Integrated Model for Plumes and Atmospheric Chemistry in Complex Terrain. Environmental Research Associates, Inc., Thousand Oaks, CA. 71 pp. 1978.

Presented the Integrated Model for Plumes and Atmospheric Chemistry in Complex Terrain (IMPACT), a three-dimensional grid model for calculating the impact of pollutants, either inert or active, in simple or complex terrain, emitted from either point or area sources. Claimed considerable success and wide acceptance of the model. (see Sklarew & Tran, 1979).

1978 Lilly, D. K. A Severe Downslope Windstorm and Aircraft Turbulence Event Induced by a Mountain Wave. JAS 35:59-77. 1978.

Presented a detailed analysis of the large-scale, mesoscale, and turbulent-scale features of a major downslope windstorm. The effects of blocking caused lateral separation of different layers and net descent of air crossing the Colorado Rocky Mountains.

1978 Klemp, J. B. and D. K. Lilly. Numerical Simulation of Hydrostatic Mountain Waves. JAS 35:78-107. 1978.

Developed a numerical model for simulating the flow of stably-stratified, nonrotating air over finite-amplitude, two-dimensional mountain ranges. Special attention was paid to the accurate modeling of internal dissipation and lateral propagation of wave energy out of the model. The model was effective in simulating the structure of two observed cases of strong mountain waves with very different characteristics.

1978 Smith, R. B. A Measurement of Mountain Drag. JAS 35:1644-1654. 1978.

Determined the pressure drag on the Blue Ridge Mountains near Harpers Ferry, WV by measuring the pressure on each side of the ridge. During the first two weeks of January 1974, pressure differences were typically 0.5 mb across the ridge. The measured drag seemed to be associated with the blocking of the surface flow upstream, a condition which occurs most frequently in stable nighttime conditions.

1978 Barry, R. G. and H. B. de Saussure: The First Mountain Meteorologist. BAMS 59:702-705. 1978.

Reviewed the contribution of Horace Benedict de Saussure, who late in the 1870s, determined that in the daytime, the air over valleys was cooler than over the mountain slopes at the same altitude.

1978 Mason, P. J. and R. I. Sykes. A simple Cartesian Model of Boundary Layer Flow Over Topography. J.C. Phy. 28:198-210. 1979.

Presented a simple method for including no-slip, irregular boundaries into a Cartesian numerical model. The method was a simplification of existing methods for dealing with irregular boundaries and was shown to be effective when the resolution requirements were satisfied.

1978 Miller, C. W. An Examination of Gaussian Plume Dispersion Parameters for Rough Terrain. Atmos. En. 12:1359-1364. 1978.

Discussed how values of lateral and vertical dispersion parameters, $\sigma_y(\chi)$ and $\sigma_z(\chi)$, for relatively flat, smooth terrain could be revised for use in complex terrain. Compared results to field measurements.

1978 Wooldridge, G. L. and M. M. Orgill. Airflow, Diffusion, and Momentum Flux Patterns in a High Mountain Valley. Atmos. En. 12:803-808. 1978.

Performed a statistical evaluation of circulation features and turbulence in relative Lagrangian coordinates, using a series of pairs of super-pressured balloons released in a high mountain valley of central Colorado. Results revealed a monotonic increase of diffusivity coefficients and momentum fluxes with height to the level of the surrounding peaks and ridges.

1978 Ookouchi, Y., M. Urgy, and R. Sawada. A Numerical Study of the Effects of a Mountain on the Land and Sea Breezes. JMSJ 56:368-385. 1978.

Studied the thermal and dynamical effects of a mountain on land and sea breezes with emphasis on the growth, decay, and extent of the circulations. A two-dimensional model was applied in three situations: 1) no mountain; 2) an insulated mountain; and 3) a heating mountain.

1979 Graham, N. E., G. H. Taylor, R. L. Peterson, P. C. Sinclair, J. W. Frey, and T. C. Koss. An Analysis of Terrain-Induced Aerodynamic Effects Near the Kingston Steam Plant, Kingston, Tennessee. AMS-Fourth Atmos. Diffusion Conf. pp. 113-116. 1979.

Examined local terrain-induced flow disturbances on pollutant concentrations from the former (76- and 91-m) and present (305-m) stacks. Supplemented investigation with a wind tunnel study. The modeling results indicated that during periods of strong northwest winds the terrain upwind of the generating station induced an increase in both horizontal and vertical turbulence in the downstream flow field. The effect extended to a height of at least 600-m above ground. The disturbances acted to restrict plume rise and increase the vertical spreading.

1979 Spangler, T. C., G. R. MacRae, and E. L. Hovind. Impact of Coal-Fired Plant Emissions on the Air Quality in Huntington Canyon, Utah. AMS-Fourth Atmos. Diffusion Conf. pp. 117-121. 1979.
Found, using five air quality monitors in the vicinity of Huntington Canyon on a continuous basis for four years that the highest three-hourly SO_2 concentration was 444 $\mu g\ m^{-3}$ and the highest twenty-four hour concentration was 183 $\mu g\ m^{-3}$. Even when these values were scaled for full-load conditions, the National Ambient Air Quality Standards for SO_2 were not violated.

1979 Ruff. R. E. The Influence of Rough Terrain on Pollutant Dispersion and Transport from a Geothermal Power Complex. AMS-Fourth Atmos. Diffusion Conf. pp. 122-127. 1979.
Made a preliminary charterization of the near-surface transport and dispersion in a geothermal area in complex terrain 80 miles north of San Francisco.

1979 Steffen, D. E., G. M. Hidy, L. K. Wang, and E. A. Berman. The Geysers Geothermal Area Emissions and Aerometric Data Base and Air Quality Analysis. AMS-Fourth Atmos. Diffusion Conf. pp. 128-134. 1979.
Discovered that the winds at the top of a ridge appeared to be driven by meso- or synoptic-scale influences, while the flow in the valleys was influenced largely by terrain discontinuities and inhomogeneities in the surface heating. Summarized the weather conditions typically associated with high H_2S concentrations. Demonstrated the marked temporal and spatial changes which occur over complex terrain by presenting plots of the wind direction during a two-hour period.

1979 Howard, E. A. and D. G. Fox. Modeling Mountain-Valley Airsheds. AMS-Fourth Atmos. Diffusion Conf. pp. 182-188. 1979.
Described a simple box model which is being developed to evaluate the particulate matter pollution due to wood burning in valleys.

1979 Issacs, R. G., A. Bass, and B. A. Egan. Application of Potential Flow Theory to a Gaussian Source Diffusion Model in Complex Terrain. AMS-Fourth Atmos. Diffusion Conf. pp. 189-196. 1979.
Incorporated theory on plumes imbedded within potential flow fields in a Gaussian point source model to calculate maximum ground-level concentrations under neutral conditions. Indicated results were preliminary and that the investigation was being expanded.

1979 Sklarew, R. C. and V. A. Mirabella. Experience in Impact Modeling of Complex Terrain. AMS-Fourth Atmos. Diffusion Conf. pp. 205-212. 1979.

The model, IMPACT (Integrated Model of Plumes and Atmospherics in Complex Terrain), was applied over thirty data sets from over a dozen locales for six regions in California. Summarized the results describing the successes and listed caveats of the model.

1979 Banta, R. and W. R. Cotton. Horizontal and Vertical Structure of Diurnal Boundary Layer Flow Patterns Over Mountainous Terrain. AMS-Fourth Atmos. Diffusion Conf. pp. 217-224. 1979.

Conducted detailed three-dimensional boundary layer flow studies over a flat plateau surrounded by mountains in the Colorado Rockies. Encountered a nocturnal drainage wind, a morning upslope wind, and an afternoon surfacing of the gradient winds aloft. The surfacing of the afternoon wind flushed pollutants out of the valley on a daily basis.

1979 Smith, D. B. and R. B. Ruch, Jr. Comparative Performance in in Complex Terrain of Several Air Quality Impact Assessment Models Based on Aerometric Program Data. AMS-Fourth Atmos. Diffusion Conf. pp. 225-228. 1979.

Discovered that the EPA Valley Model calculated pollution concentrations much higher than those observed in the Penobscot River Valley of Maine. Reported that calculations made by a modified EPA algorithm gave more accurate results than the Valley Model.

1979 Minott, D. H. and D. L. Shearer. Measurements of Vertical Dispersion Rate in Deep-Valley Terrain. AMS-Fourth Atmos. Diffusion Conf. pp. 229-236. 1979.

Conducted experiments in three deep U-shaped valleys and a fjord in Norway. A total of 53 experiments were conducted using oil-fog and FP tracers. Following standard procedures, vertical dispersion coefficients (σ_{zt}) were determined. Authors concluded 1) the mean deep-valley σ_{zt} superimposed upon the Pasquill-Gifford (P-G) σ_z curves, however, they comprised a narrow band in comparison to the range of the Pasquill-Gifford curves; 2) the P-G dispersion rate for Class A (extremely unstable) and Class G (extremely stable) conditions were not observed in the deep-valleys; 3) the vertical dispersion rate in a deep-valley was similar to that over flat land having similar surface roughness; 4) the deep-valley σ_{zt} curve for unstable conditions exhibited decreasing slope with distance, contrary to the P-G σ_z curves for Classes A and B stability, but in agreement with the Hosker-Smith σ_z curves for unstable conditions; 5) stability classes determined by vertical temperature differences indicated sigmas that were off by a factor of two or three from the actual σ_{zt} values during unstable and neutral conditions;

6) the vertical dispersion rate in the fjord during neutral conditions was one-quarter of that observed over land and much less than the P-G F rate.

1979 Wan, P. K. Calibration Program for Complex Terrain Diffusion Model. AMS-Fourth Atmos. Diffusion Conf. pp. 237-240. 1979.
Analyzed 571 observations collected over a two-year period in the vicinity of a fossil fuel power plant in the Hudson River Valley. Concluded that 1) the flow characteristics of regions with complex terrain differ significantly as a function of topographic details and meteorological conditions and 2) thermal and topographic effects appeared to increase diffusion rates in regions of complex terrain over those which might be expected over level terrain.

1979 Arya, S.P.S. and M. S. Shipman. A Model of Boundary Layer Flow and Diffusion over a Ridge. AMS-Fourth Atmos. Diffusion Conf. pp. 584-591. 1979.
Conducted an investigation in a wind tunnel on the influence of a two-dimensional ridge on the flow and diffusion in a neutral boundary layer. The separation bubble behind the ridge was found to extend to a distance of 13h (h = ridge height) in the longitudinal direction and up to about 2.5h in the vertical. The cavity was characterized by a greatly reduced, but circulating mean flow and high intensities of turbulence.

1979 Meroney, R. N. Field Verification and Laboratory Simulation of Airflow Patterns in Complex Terrain. AMS-Fourth Atmos. Diffusion Conf. pp. 592-595. 1979.
Compared laboratory simulation results to available field data by means of statistical correlation and scatter diagrams and concluded laboratory simulations compared very well with field data.

1979 Koch, R. C., W. G. Biggs, D. Cover, H. Rector, P. F. Stenberg, and K. E. Pickering. Power Plant Stack Plumes in Complex Terrain - Description of an Aerometric Field Study. EPA-600/7-79-010a. ESRL, Research Triangle Park, NC. pp. 168. 1979.
Described the monitoring network established and operated in the vicinity of the 712-megawatt, coal-fired, Clinch River, Virginia Steam Power Plant as part of an investigation of transport and dispersion in complex terrain.

1979 Thompson, R. S. Dispersion of Sulfur Dioxide from the Clinch River Power Plant - A Wind Tunnel Study. EPA-600/4-79-052, ESRL, Research Triangle Park, NC 1979.

Simulated the topographic features of an area in which a diffusion investigation was conducted. The most significant influences of terrain on the plume, in this wind tunnel study, were found to be frequent downwashing and an angle of about 30° to the mean wind direction for the plume's initial release. These phenomena were produced by the hills just upwind and downwind of the stacks. Ground-level concentrations measured at positions corresponding to field sampling sites compared well with field-measured values. Comparisons of concentrations measured above the model surface with helicopter field measurements did not show good agreement.

1979 Ellis, H. W. and P. C. Liu. Comparison of Predicted and Measured Concentrations for 54 Alternative Models of Plume Transport in Complex Terrain. Presented at APCA Annual Meeting, June 24-29, 1979. Cincinnati, OH. 16 pp.

Compared measured and predicted maximum short-term SO_2 concentrations for 54 alternative models and identified several models that accurately predicted the highest 24-hour SO_2 concentrations. Each model required an adjustment in the plume centerline location as the plume was transported downwind in rising terrain. These same models overpredicted by substantial margins the highest measured three-hourly SO_2 concentrations. Limitations in the emissions data were the suspected cause of the overpredictions.

1979 Whaley, H., G. K. Lee, and J. G. Gainer. The Behavior of Buoyant Merging Plumes in the Rocky Mountain Foothills. Presented at APCA Annual Meeting, June 24-29, 1979. Cincinnati, OH. 16 pp.

The behavior of highly-buoyant, low-momentum plumes from two natural gas sulfur extraction plants located in the foothills of the Canadian Rockies was strongly influenced by geographic factors including regional topography and chinook winds. In addition,

1) The plume axis elevations did not exhibit the usual leveling-off tendency in neutral conditions. Derived plume rise values were generally lower than estimated by the Briggs' neutral formula but agreement with the two-thirds power law dependence with downwind distance was observed. This conclusion reinforces findings made elsewhere in Canada in different climatic regions.

2) The derived standard deviations of plume spread showed significant differences from those indicated by Pasquill. Local channeling of airflow resulted in reduced plume width at the plant situated closest to the mountains with horizontal standard deviation values, in general, less than Pasquill Class F. For the smaller plant, located farther from the mountains, the horizontal standard deviation data were in excess of Pasquill Class A and agreed with studies made in flatter terrain. Vertical turbulence induced by the mountains persisted over the entire dispersion zone and resulted in enhanced vertical mixing with vertical standard deviations corresponding to Pasquill Class B rather than Class D; and

3) Application of the standard methods of predicting in the Rocky Mountain foothills which are subjected to frequent chinook winds, resulted in gross errors in estimated ground-level impact concentrations.

1979 Norton, C. and A. Roffman. Wind Flow Patterns in Complex Terrain of Allegheny County, Western Pennsylvania. Presented at APCA Annual Meeting, June 24-29, 1979. Cincinnati, OH. 13 pp.

Compared wind directions at the two major airports situated on plateaus in the Pittsburgh area with those at nine locations in the three river valleys which transect the area. Concluded that the airport winds represented the mesoscale flow but not the flow in the valleys. Flows in the valleys were generally in accord with the orientation of the valley in the immediate area.

1979 Chan, M. W. A Tracer Experiment to Determine the Transport and Dispersion of an Elevated Plume in Complex Terrain. Presented at APCA Annual Meeting, June 24-29, 1979. Cincinnati, OH. 13 pp.

In a detailed two-day study discovered that

1) Local forces were responsible for the transport and diffusion of pollutants during nighttime and early morning hours when the synoptic pressure gradient was weak (the synoptic wind flow was not established in the valley until after mid-day);

2) When the plume was released within a layer of very stable air in complex terrain, the plume followed constant potential temperature surfaces, which followed the contour of the ground (it did not just fan out and stay at the same elevation above mean sea level);

3) Fumigation of the plume did not result in high concentrations when measurements were averaged over a period of one-hour or more;

4) When the surface-based inversion was shallow, the plume lofted above the inversion and pollutant concentrations at the surface were miniscule; and

5) When the plume was released in a neutral layer, the plume centerline followed the contour of ground surface as it traveled downwind.

1979 Sklarew, R. C. and K. T. Tran. Air Pollution Modeling in Mountainous Terrain. Paper presented at APCA Annual Meeting, June 24-29, 1979. Cincinnati, OH. 14 pp.
Discussed air pollution models based on a simplified analytical solution (Gaussian model) and those based on a partial differential equation describing conservation of pollutant mass (grid model). The Gaussian model, while used extensively, was found to be limited in its direct applicability. Thus, for application in mountainous terrain the Gaussian model must be modified to account for wind channeling, increased dispersion, and elevated receptors. Grid models, such as the Integrated Model Plumes and Atmospherics in Complex Terrain (IMPACT) model, can readily account for mountainous terrain effects. IMPACT achieved the preferred generality and flexibility since it is a collection of models to calculate wind fields, diffusion, and pollutant transport.

1979 Hunt, J.C.R., J. S. Puttock, and W. H. Snyder. Turbulent Diffusion from a Point Source in Stratified and Neutral Flows Around a Three-Dimensional Hill-Part 1. Diffusion Equation Analysis. Atmos. En. 13:1227-1240. 1979.
Solved the advective diffusive equation for flow around a three-dimensional hill using an eddy diffusivity formulation. Showed how source positions on and off the centerline affect the trajectories and splitting of impinging plumes and the value and position of the maximum surface concentration on a hill.

1979 Inoue, O. Resonance of Lee Waves of a Stratified Flow Over Two Barriers. JMSJ 57:21-28. 1979.
Studied resonance of lee waves produced by two barriers in a two-dimensional channel with special regard to therelationship between the amplitude and the distance between the two barriers. The study dealt with a two-dimensional, steady flow in a stably stratified, incompressible, and inviscid fluid. The governing equation was solved analytically.

1979a Mason, P. J. and R. I. Sykes. Flow Over an Isolated Hill of Moderate Slope. QJRMS 105:383-395. 1979.
Extended the two-dimensional theory of Jackson and Hunt for turbulent flow over a shallow ridge to three-dimensional topography. Compared the results to the theory of flow over a ridge and wind observations from a nearly-circular 130-m hill (see Mason and Sykes, 1979b).

1979 Smith, R. The Influence of the Earth's Rotation on Mountain Wave Drag. JAS 36:177-180. 1979.
Considered the two-dimensional flow of a stratified rotating fluid over a ridge using the linear theory model of Queney (1979). A general expression for the wave drag was derived. As progressively wider mountains were considered, the wave drag decreased and the flow became more nearly geostrophic.

1979 Mainin, P. C. and B. L. Sawford. A Model of Katabatic Winds. JAS 36:619-639. 1979.
Employed a hydraulic approach in which the detailed vertical structure of the flow was replaced by a quiescent stably-stratified environment and an equivalent flowing layer which was subject to sustained layer cooling, surface stress, and interfacial entrainment. A scaling which contained much of the parametric behavior was found. Results showed that interfacial entrainment was the dominating retardation mechanism of the flow and that surface stress might be relatively unimportant. The model gave satisfactory quantitative agreement with the limited field data available.

1979b Mason, P. J. and R. I. Sykes. Three-Dimensional Numerical Integrations of the Navier-Stokes Equations for Flow Over Surface-Mounted Obstacles. J. Fl. Mech. 91:433-450. 1979.
Numerical integrations of the Navier-Stokes equations for flow past a smooth, three-dimensional, surface-mounted obstacle were presented. The variation of the flow with Reynolds Number and with geometric ratios such as the maximum slope of the obstacle were investigated. The separated flow was investigated using visualizations of the surface-stress patterns and particle trajectories through the flow (see Mason and Sykes, 1979a).

1980 Williams, W. T. Air Pollution Disease in California Forests. A Base Line for Smog Disease on Ponderosa and Jeffrey Pines in Sequora and Los Padres National Forests, California. ES&T 14:179-182. 1980.
Concluded that there was air pollution damage to lower elevation yellow pine forests in the mountainous area downwind of the Central Valley. The damage was reported to be widespread. The results offer support to the contention that impaction occurs in a valley

1980 Bradley, E. F. An Experimental Study of the Profiles of Wind Speed, Shearing Stress and Turbulence at the Crest of a Large Hill. QJRMS 106:101-123. 1980.

Measured, under neutral conditions, the turbulent wind structure on a 100-m tower at the crest of a hill of height h = 170 m. A local velocity maximum, or "jet", was observed at about h/5 m. Below the jet, the ratio of the increase in wind speed to the upwind value at the same height was 1.07 and almost independent of the height near the surface.

The r.m.s. turbulence components σ_u, σ_v and σ_w were also approximately doubled near the surface, but whereas σ_u and σ_v both decreased with height, the surface increase in σ_w extended over the height of the entire measurements.

1980 Pickering, K. E., R. H. Woodward, and R. C. Koch. Power Plant Stack Plumes in Complex Terrain. Data Analysis and Characterization of Plume Behavior. EPA-600/7-80-008, USEPA, Research Triangle Park, NC. 333 pp. 1980.

Analyzed data collected during a 16-month field program conducted near the Clinch River Power Plant in western Virginia. The purpose was to characterize the behavior of a plume in complex terrain. The study provided an adequate data base for the evaluation of plume behavior in complex terrain.